CONVR 2011

November 3+4, 2011, Bauhaus-Universität Weimar, Germany

Proceedings of the 11th International Conference on Construction Applications of Virtual Reality 2011

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Hans-Joachim Bargstädt | Karin Ailland

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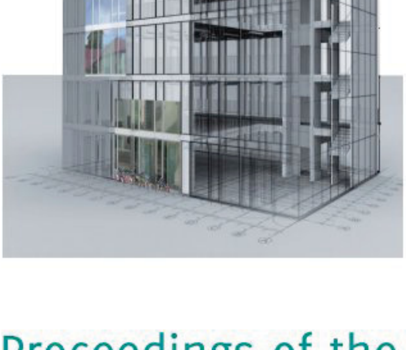

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PREFACE

We are very pleased to hold the 11th International Conference on Construction Applications of Virtual Reality (www.CONVR2011.com) this year in Germany. The CONVR started in 2000, and the conferences have been held in Teesside, UK (2000), Chalmers, Sweden (2001), Blacksburg, VA USA (2003), Lisbon, Portugal (2004), Durham, UK (2005), Orlando, Fl USA (2006), Penn State, Pa USA (2007), Kuala Lumpur, Malaysia (2008), Sydney, Australia (2009) and Sendai, Japan (2010). So we are proud to invite you this year to Weimar, the European cultural capital of 1999 and the founding city of the worldwide known Bauhaus.

The Bauhaus school was founded by Walter Gropius in 1919 in Weimar. In this period other famous modern architects, artists and craftsmen like Johannes Itten, Paul Klee, Wassily Kandinsky and László Moholy-Nagy were active and teaching in Weimar. The "Bauhaus" was the concept of harmony between the function of an object or a building and its design. It tried to unite arts and crafts in order to generate added value to our living environment.

Thus by transferring the basic idea and the ideals of the former Bauhaus to current time technology, we are challenged by concepts of developing new media and using new media tools and knowledge for architectural and engineering purposes. Also these new media, especially virtual and augmented reality, facilitate the transfer of our ideas to the customer, to the users of modern real estates and infrastructure buildings, to the inhabitants of our sheltered urban spaces.

In response to our Call for Papers we received 123 abstracts from authors of 23 different countries. 80 papers have been accepted by the International Scientific Committee, based on a two phase review process. In the first phase two experts reviewed the abstracts, accepting, accepting with commentaries or rejecting the abstracts. In the second phase again two randomly assigned experts reviewed the full papers. Finally 76 papers were accepted by the committee, they – and the key note papers – will be presented during the conference.

Hans-Joachim Bargstädt (Chair Bauhaus-Universität Weimar)

Karin Ailland (Co-Chair Bauhaus-Universität Weimar)

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We would like to express our sincere gratitude to all authors for their enthusiasm in contributing their research as published in the proceedings and as presented during the conference. We are also deeply grateful for the big effort, which the International Scientific Committee put into the reviewing and consulting process ahead of the conference.

For the numerous support in organizing the conference and composing the final program layout we give our warm thanks to the CONVR2011 organizing committee. They have helped us in selecting a suitable pattern through the vast amount of very interesting research subjects within the scope of the conference. Also many helpers from the Bauhaus-Universität Weimar as well as others from the service units at the Weimarhalle will help to make the conference a memorable event.

We very gratefully thank our sponsors for supporting the CONVR2011 and the idea of exchanging ideas and results on construction applications of virtual reality. They are:

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MULTI-USER VIRTUAL REALITY

Bernd Fröhlich, Prof. Dr.
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ABSTRACT: *This talk presents the design and implementation of a novel stereoscopic six-user display wall and introduces collaborative pointing, navigation and object manipulation techniques for immersive virtual worlds.*

KEYWORDS: *immersive virtual reality, stereoscopic displays, 3D interfaces.*

1. A Stereoscopic Display for Six Users

Perspective projection in combination with head tracking is widely used in immersive virtual environments to support users with a correct spatial perception of the virtual world. However, most projection-based stereoscopic systems show a correct perspective view for a single tracked viewer only. Other users share the same view, but they look at the images from a different location than the tracked viewer, and thus they perceive a distorted virtual world. This severely limits the suitability of projection-based stereoscopic systems for multi-user scenarios, particularly in application domains where collaborative 3D-interaction of a group of experts is needed.

Fig. 1: The six-user display. Each user is tracked and perceives a separate stereoscopic image.

We developed a new projection-based stereoscopic display for six users (Kulik et al, 2011), which employs six customized DLP projectors for fast time-sequential image display in combination with polarization (Figure 1). Our co-located six-user virtual reality system enables natural collaboration in shared virtual worlds by providing multiple tracked users with individual 3D images. Users can talk to each other, gesture and point into the virtual scenery as if it were real. The possibility to hand over virtual tools between users is another important improvement over single-user systems.

Direct pointing without using a virtual pointer is the most natural and a highly appreciated way of interacting with virtual objects. When comparing pointing at virtual objects to real-world pointing we found that features larger than two centimeters can be safely referenced by bare-finger pointing. For smaller virtual objects we recommend the use of a virtual pointer, since otherwise tracking and calibration inaccuracies may result in miscommunication between users (Salzmann et al, 2009).

While pointing can be used for the collaborative inspection of virtual 3D models in a multi-viewer system, such real-world actions also result in real-world problems: One might want to show a virtual object to colleagues, but the object might be occluded from their respective viewpoints. To solve this problem in reality, people have to walk around the occluding objects to obtain a suitable viewing position. A common behavior is to move close to the person who is pointing in order to see the specified object (e.g. by looking over his shoulder), which can result in a physical proximity of users that does not comply with social protocols of formal presentations. We equip users with augmented viewing capabilities for allowing them to look through objects if another person points at an occluded target. These virtual x-ray vision techniques reduced the number of cases in which users needed to get very close or even bump into each other. Our findings also showed that they can maintain a socially convenient distance for most of the time while moving much less than without applying these techniques (Argelaguet et al, 2011).

Navigation is a central functionality in virtual reality applications. However, navigating a group of six users through a virtual world leads to situations in which the group will not fit through spatial constrictions. We developed augmented group navigation techniques to ameliorate this situation by fading out obstacles or by slightly redirecting individual users along a collision-free path. While redirection goes mostly unnoticed, these techniques temporarily give up the notion of a consistent shared space. Our user study confirms that users generally prefer this trade-off over naïve approaches (Kulik et al, 2011).

Providing six users with individual stereoscopic images significantly improves the usability of virtual reality displays such that they can be successfully employed in many more application domains, e.g. architecture, civil engineering, museums and the automotive industry. Also, stereoscopic TVs and stereoscopic multi-player gaming just won't be accepted without support for multiple users. However, producing 3D content for such systems gets more complex – in particular if the real world is involved. We will discuss the limitations and future developments of our approach, the resulting challenges for supporting the interaction of a group of users and the implications for 3D content production.

2. Rererences

Argelaguet, F., Kulik, A., Kunert, A., Andujar, C., Froehlich, B. (2011) See-through Techniques for Referential Awareness in Collaborative Virtual Reality, International Journal of Human-Computer Studies (IJHCS), Vol. 69, No. 6, 387-400.

Kulik A., Kunert A., Beck S., Reichel R., Blach R., Zink A., Froehlich B. (2011). C1x6: A Stereoscopic Six-User Display for Co-located Collaboration in Shared Virtual Environments. To appear in Siggraph Asia 2011 and ACM Transactions on Graphics (TOG).

Salzmann H., Moehring, M., Froehlich, B. (2009). Virtual vs. Real-World Pointing in Two-User Scenarios Proceedings of the 2009 IEEE Virtual Reality Conference (IEEE VR 2009), 127-130.

DEVELOPMENT OF SERIOUS GAME ENGINE APPROACH FOR H&S TRAINING FOR THE CONSTRUCTION INDUTRY.

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Abstract: *The number of accidental deaths and injuries reported each year in the construction industry is significantly greater than that of other industries. This research paper is a part of an ongoing effort to improve and enable H&S (Health and Safety) training on construction sites through the use of serious gaming technology. Serious games provide an avenue for people to experience what occurs on a construction site and possibly develop hands-on skills before they enter a live construction site. A limited number of tools have traditionally been designed around the assumption of users engaging with preset construction scenarios with the goal of learning specific skills or behaviours that are important when interacting with the site for real. However, these have been proven to be of limited use in the industry. Also, 4D (3D plus time) and 5D (3D plus time plus cost) planning and visualisation tools can help expand the horizons of training games. By merging virtual training environments with a 4/5D planning, the range of potential knowledge the game can impart can be significantly increased. This research paper is involved in exploring how a cross-pollinisation of these two methodologies/techniques can yield a richer environment for transferring skills and knowledge. This paper explores the creation of a multi-user virtual environment capable of providing health and safety training and orientation to groups of trainees before they step foot on site.*

Introduction

To combat this perceived lack of H&S skills in the construction industry, this research is proposing the development of a virtual training environment to provide construction planners and middle management with a means to experience H&S issues on construction site. This will be achieved through provide new training tools that involve 'human centric design' approach aiming at integrating 5D (3D plus time plus cost) modelling with H&S issues that have significant influence on the workers wellbeing and site progresses.

This research is interested in exploring 'serious game engine' as a solution to improve construction managers and workers' understating of construction processes. A 'series game engine' can provide virtual training involves using computer based tools to create an interactive simulation that can impart knowledge and skills to the user. Commonly training courses are currently focusing on scenario or exercise based learning exercises. In transitioning to a virtual environment new possibilities have opened up in the way health and safety and site training can be conducted that have been insufficiently explored to date.

Many construction companies have the capability to produce their building plans in the format of 3D models, both for site design and use with project management tools like 4/5D planning packages. This research was driven by how those existing techniques/tools could be integrated with virtual training environments. The approach that this research is striving to provide is one that is as similar to the construction site experience. Other virtual environments seek to replicate this through optical tricks to increase immersion. The goal here is to achieve that effect through a robust environment that is identical to an actual construction site. Other virtual tools aim for visual immersion, this environment is aiming for spatial immersion. In this context, it is hypothesised that 'A sandbox style training arena has advantages over linear training scenarios for virtual training."

The key focus of this research is on the application of a common virtual game design framework as part of a health and safety training tool for the construction industry. Previous literature concluded that there is a distinct lack of examination of game-play elements in the field of serious games (Portnow, Floyd and Theus 2010). This research will explore this further and how it would impact on the design and pedagogy of serious games.

Objectives of the research work

The aims of this research are to explore the use of trainee led scenarios in virtual training environments and how emergent learning and human centric design can improve user immersion and awareness of health and safety. To test the effectiveness of the research hypothesis, it will involve the development of an interactive multi-user virtual environment that can be used to generate and implement a H&S training experience for planners and site managers. This includes the identification and integration of beneficial learning technologies that have been developed in other industries or fields of research.

The objectives are:

- To develop a methodology for implementing a 4/5D construction site within a virtual world.
- To develop a structure and protocol to implement emergent learning behaviour as part of the virtual learning environment using serious game engine.
- To produce a framework or methodology that could be used to implement the knowledge created by this research into other construction sites using these tools.

State of the art review

Learning models in engineering education can be improved by including IT support into existing learning frameworks (Li 1997). This research is attempting to combine the positive educational aspects of serious games with the site management potential of 4/5D modelling. By merging 4/5D principles with the design of virtual training scenarios it is hoped that a greater feeling of verisimilitude can be created in the minds of the users. Virtual prototyping of construction operations have been shown to be of beneficial use to construction operations (Li et. al. 2005). This type of virtual model tends to be a top down affair, focusing on management and planning. Could this be useful when oriented from a bottom up perspective? By taking the site down to a personal scale and using it for different levels of employees' training, they can proactively experience the site and become aware of some of the potential problems and pitfalls they face on site in a safe environment. In this research, the inclusion of game-play frameworks specifically that of open world gaming, are being explored to determine if they can also bring similar benefits to engineering training.

With an evolving 3D model, the environment can react to site changes to give an accurate view of the site at any time. With a traditionally designed environment, changing the model to react to site changes requires a substantial amount of remodelling to show site progress. Incorporating 4/5D modelling into the design of the virtual training environment should decrease the work load of implementing schedule based site changes. This can be done by linking virtual 3D models to a site schedule that will enable 4-5D modelling. Virtual worlds already contain some of the required infrastructure to perform this function. It is possible to create environments that user can change and explore simulated construction processes over time.

By constructing a dedicated scenario for the training or education using 4/5D models and 'human centric desig', the environment becomes more focused. It gives a greater ability to structure the learning outcomes to the specific lessons that the program wants to impart. The immediacy of this design structure makes it popular for constructing directed tasks such as learning activities. This approach allows for scenarios to be created efficiently and has been the focus of a significant amount of research into. The structured nature of this type of virtual learning is also similar to classroom exercises or workshops, which provides a certain transferability of related experiences. This is will be dubbed in this paper as non-linear game-play.

Non-linear game-play scenarios are starting to be explored for training within a construction context. Even so current efforts are still rooted in scenario based design (Lin, Wook Son and Rojas 2011). This suggests that a sandbox approach is something that could benefit the industry, if the open world nature provides valuable learning outcomes that can compete with a more focused scenario based game.

The primary inspiration behind the creation of an emergent virtual learning environment is that of popular sandbox style video games like the Grand Theft Auto series. These types of games are usually structured around a mission hub where the game designers place content that they believe will entertain their audience. This hub is then designed as a 'believable environment' with a number of different ways that players can progress between the individual missions, in the GTA series this takes the form of a sprawling urban city with a simulated populous. The mission hub also includes a number of mini games or side quests that players can engage with or not, at their discretion. The goal with these additional game play elements is to provide more compact contents than a full mission and to encourage players to interact with the mission hub as an actual environment.

From a pedagogical perspective a scenario based design provides a more immediate gateway to learning. The environment can be set out so that when users enter they can encounter learning challenges to engage them in the activity. Further the layout of the environment allows users to gradually explore the virtual world and experience tiered challenges that build upon knowledge previously gained from the scenario. With a sandbox style emergent learning environment there are different pedagogical challenges to face. The environment has a different structure and flow due to its open plan nature. When users are interacting with the environment it should allow for an element of free roaming exploration as part of the learning experience. The environment should be approachable through different directions; the learning challenges within the virtual world should not be on a linear scale of difficulty.

The very fact of trying to provide educational content in a 3D immersive space faces some new pedagogical challenges (de Freitas and Neumann 2009). The learning community that has developed around the area of serious games has a number of limitations. The common pedagogical base for developing these types of games is usually rooted in classroom thinking. This leads to game development being constrained to the types of activities already in use in classroom environments, typically that of simple role-play activities or that of highly focused demonstrations. The way people approach interactive media means this pedagogy has stumbling blocks that a more game-based approach can be avoided by keeping the engaging elements of the medium and then providing educational content as part of the game-play (Savin-Baden 2007).

Educational tools based around site management and health and safety issues in the construction industry are also having benefits divorced from an educational context (Goedert et. al. 2011). The very nature of the industry means that any sufficiently expansive training tool can also have benefits for the planning and management from a design or planning perspective. If a training tool allows users to experience health and safety risks on an accurate replica of a site then the planner or designer can use the same tool to explore the site. In this manner they can examine their building for any problems with site layout or access that are less obvious from even a 3D or 4/5D model.

Research Methodology

The research is intending to explore the potential for using interactive 4/5D environments as a training tool for the construction industry. This will involve the generation of a test environment to provide feedback on the effectiveness of the environment and supporting design theory. This research is following a qualitative method toward the analysis of the generated data.

The research problem revolves around the potential benefits toward adopting an IT centric training style to provide training to the construction industry. Solving this will involve the development of a pedagogical model suitable to the needs of this industry. To build up this model this research is progressing on the assumption that a virtual construction site processes replica will provide a greater immersive experience than more targeted serious gaming scenarios.

This research intends to examine the areas of health and safety in construction, human centric design, virtual learning environments, web-based tools, emergent learning and 4/5D planning as part of a means to building up a sandbox virtual environment that will reflect a building site over its working life. The pedagogy of development for the virtual environment is focused on allowing the virtual environment to provide some of the learning outcomes as opposed to purely scenario driven learning outcomes.

Design of the Virtual Environment

This research is built around the assumption that an expansive and fully realised virtual training site provides a greater educational benefit than an intentionally constrained virtual training scenario. In order to achieve this, it is necessary to be able to create a full scale site within the virtual environment. In this instance the decision was made to make a true to life replica to ensure that the virtual model is a truly open world environment. To do this a construction company, Morgan Ashurst, agreed to be part of a case study and a complete set of site plans was acquired as well as a project schedule. In addition to these a fire evacuation diagram was also obtained. This is an important piece of information for generating a replica site because of the fact that it includes temporary structures in the site layout. These temporary structures are important to provide the feeling of a living construction site but aren't included in normal design schematics.

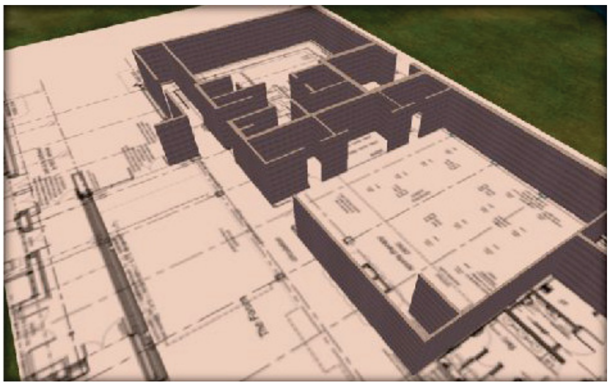

Fig. 1: Building Plan

To recreate this virtual site 'OpenSim' environment was used. Primarily this was selected because of inbuilt functionality that supports multiple users interacting with both the environment and each other. The building schedules and 3D models were imported into the environment. The model was then built up in a series of sections that reflected construction processes, 4/5D modelling. An example of the way this was done is shown in figures 1 and 2. By building the environment in this fashion it allows the site to be linked with the timing of the schedule. This will be exploited through the use of 'Holodeck' technology. This is a process whereby the environment within OpenSim can be changed from one world to another (timeline of the construction process) through a simple command. By linking the individual models to the start and finish dates of each task this technology can be used to display how the site appears according to wherever on the timescale the simulation or scenario requires.

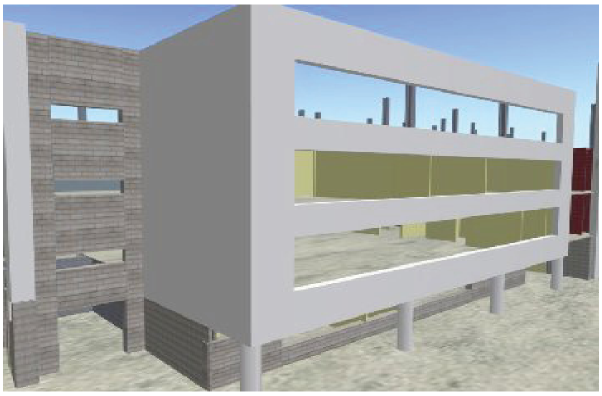

Fig. 2: 3D Environment

To add H&S training to the environment, a number of linked training scenarios have been developed. These scenarios serve to illustrate the potential usage of this tool by allowing trainees to interact in situ in a manner similar to conditions as they would be on-site. They also form a part of the evaluation criteria for the environment. By using predefined scenarios the effectiveness of the learning experiences being generated can be examined. These scenarios are envisioned as small group exercises with an instructor present to evaluate trainee performance. In addition, the users will be given a feedback sheet where they can record their experiences. This will allow a measurement of both their comparative performance and their personal reactions to the training style.

The first scenarios will involve workers laying the foundations of the construction site and engaging in initial building work. This scenario is designed to introduce users to the environment and the interface of the program and so focuses on the first stages of construction work to simplify their interactions in-world. The key training points will be selection of appropriate safety equipment and site awareness, including acknowledging warning signs and the presence of heavy goods vehicles. This will be accomplished by having the avatars of the users appear on-site as they would in reality. Then users will need to retrieve personal protective equipment (PPE) and move to their designated work area.

The second training scenario will include more site features as the construction work progresses. This will have more site features for the users to interact with, being representative of the evolving construction site and make use of the greater familiarity users have with the interface. As in the first scenario the avatars will appear on-site as if they had arrived for a new working day. This reinforces both the verisimilitude of the environment and means that they have to repeat the process of acquiring their PPE as they would when working on the real construction site. The task will involve the building up of the walls and structure of the environment. This will require manual handling activities in transporting building material from storage to a suitable working area.

The third planned training scenario continues to progress the timeline of the construction site. As with the previous scenarios the activities will be structured as if users are arriving for a new day's work. Here users will be working on the second storey of the build and will need to be aware of dangers posed by working at height. To impart this knowledge the trainees will need to construct scaffolding and erect safety railings as needed.

With regard to the training element of the project there will be a number of testing workshops to evaluate the test environments. This will involve multiple users being active in the program concurrently. In order to test the capability of the environment to impart knowledge to its users there will be both a directed session and a free session. The directed session will deal with interacting with the environment and dealing with interface issues and include the use of existing H&S training tools such as orientation videos and toolbox talks. The learning experience will be directed by in world by a user portraying the site foreman. This will allow data to be gathered on how intuitive to manipulate the environment is. The free session will consist of users being given job roles to perform and left to interact with the environment without explicit direction. This will be where the primary feedback from the effectiveness of the learning environment will be gathered.

Very few evaluation frameworks exist in the area of immersive virtual worlds (de Freitas and Oliver 2006). The areas of evaluating immersive learning has received some attention by previous researchers and provide some interesting ideas for developing evaluation criteria in an under researched field (de Freitas et. al. 2009).de Freitas et. al. 2009 research is a useful starting point for the development of feedback and evaluation frameworks that need to be developed for the testing phase of the research reported in this paper..

As part of the feedback, this research hopes to adopt some of the methods put forward by Augustin for individual skill assessments where it is practical (Augustin et. al. 2010). By giving the users a longer leash to immerse themselves in the environment their behaviour should provide data on how people will choose to interact with the software. This data will allow the refinement of the emergent learning techniques that are deployed in the environment. Both tests will be performed on the two test environments. The data from the first feeding back into the design of the second and the final testing allowing a comparison between what was aimed for and what has been accomplished.

Conclusion

This research reported in this paper is adapting the concept of serious games environments and exploring how to improve its potential as a training tool for H&S in construction. Aspects of 4/5D planning, emergent play and sandbox training scenarios are the current focus of the work. By providing an environment that is easier to understand and interact with there should be an increase in the training that can be imparted to any given user.

In addition to the consideration of emergent training opportunities the way the user interacts with the technology itself is also a potential benefit. Out of contemporary training methods practical exercises provide the most transferable skills back to the trainee. For designing a virtual training environment matching the interface to the activities performed maximises the transferability of the skills learned. This research hopes to apply these principles to design and use of user interfaces in current virtual environment tools and provide suggestions for improvement.

By designing the interface and environment in this way the lessons and experience gained using this technology will face fewer barriers in transferring into real world skills. To accomplish this there was a focus on avatar directed activities and a movement away from menu driven commands. Another aspect that has been informed by this is scenario design itself. By integrated elements of scenario design into the world design it will lessen the need for specific scenarios and allow it to function as a more realistic construction site.

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A CONSTRUCTION SYNTHETIC ENVIRONMENT INTEGRATING VISUALIZATION AND SIMULATION

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ABSTRACT: *To attract and retain industry interest, simulation must be able to capture and display the complexity of today's construction projects without requiring expert modelers. The obvious benefits of 3D visualization have led many researchers to incorporate it into construction simulation models, but while the industry explores sophisticated 3D planning and project management, many construction simulation visualization options remain based on static, post-simulation rendering. For the past two decades, the Research Team at the Hole School of Construction Engineering has been advancing the state of the art in modeling and simulation of construction operations to facilitate deployment of automated construction planning and control processes, and to provide the industry with the advanced tools to design and analyze construction operations. In this paper, we explore some of those advancements, especially in the area of construction simulation and visualization. We will focus on presenting a construction synthetic environment which integrates dynamic 3D visualization with a user-friendly process interaction simulation system to allow users to view and interact with the simulation during the scenario-based planning process.*

KEYWORDS: *Simulation; Construction management; Decision support; Automation; Tunneling; 3D CAD, Visualization*

1. Introduction

The industrial base around the world depends on infrastructure and facilities. Large-scale projects of this kind require expertise and specialization, and are planned, engineered, constructed, and operated by a segment of the construction industry we refer to as "the capital projects industry." Capital projects will account for approximately $145 billion investment in Canada in 2011(Statistics Canada 2011). Improvement in the delivery of capital construction projects therefore has the potential to greatly impact aggregate productivity and ultimately economic welfare, with estimates ranging from 5% to 15% reduction in costs, representing billions of dollars in potential savings (FIATECH 2009).

As projects become more complex, they become harder to manage using standard techniques. Experts agree that there are two components to improving the delivery of construction projects. The first involves addressing industry-level and socio-economic factors; for example, fragmentation within the industry, an incoherent supply chain, the contracting environment, regulations, the nature of work in the open field, and a general lack of process innovation. The second involves addressing project- and company-level delivery challenges, such as the dynamic and uncertain environment of construction, one-off projects and a lack of repetition, lack of industry-wide information technology standards that facilitate seamless integration and collaboration among project participants, hasty and unstructured propagation of advanced technologies and equipment without appropriate frameworks, among other issues (FIATECH 2009). Our focus in this paper is on the second set of challenges. Simulation has been shown to be a highly effective tool for dealing with many of those issues, particularly in integration with other tools (AbouRizk 2010, Wood and Alvarez 2005), but industry adoption has not kept pace with the advancements in simulation technology. To be embraced by industry, simulation must be able to capture and display the complexity of today's construction projects without requiring expert modelers.

1.1 Approaches to simulation

Whatever the tool used, developing and using a simulation model generally involves four steps: product abstraction, process abstraction and modeling, experimentation, and decision-making (AbouRizk 2010). In the product abstraction phase, the "product" – that is, the construction project – is abstracted. For example, a tunnel consists of a working shaft, the tunnel itself, and the exit shaft; these have physical dimensions, ground conditions, and design requirements which must be taken into account. Product abstractions are best suited for 3-D modeling enriched with information (i.e. BIM modeling). In the second step, the processes involved in the physical construction of each of these sections are then modeled, using logic and mathematical models. Process interaction simulation modeling has proven to be very effective in representing construction methods and operations. The model is then generally tested and various scenarios are run to study the underlying system behavior: the time it takes to complete a project, resources which are utilized, any bottlenecks which can be identified, and the behavior of the system when those bottlenecks are removed. Finally, the information generated by the simulation is used, along with industry expertise, to make decisions about how the actual project should be designed, planned, and constructed. The final two steps have benefited immensely from the advancements in user interface capabilities of today's computing technologies.

Other advancements in the development of programming languages have enabled construction simulation to become more powerful and easier to use. Proposed by Teicholz in 1963 and expanded by Gaarslev (1969), construction simulation came into its own with Halpin (1973) and CYCLONE, the first true general-purpose construction simulation tool. Further developments included COOPS (Liu 1991), DISCO (Huang and Halpin 1994), CIPROS (Odeh et al. 1992), STEPS (McCahill and Bernold 1993), ABC (Shi 1999 and Lu 2003), STROBOSCOPE (Martinez and Ioannou 1994), and Simphony (Hajjar and AbouRizk 2002). These developments were largely attempts to make construction simulation more flexible and user-friendly, incorporating drag-and-drop user interfaces and many other features. In large part, these are classified as process interaction simulation modeling tools. The current movement in the field is towards integrating simulation with other tools, especially visualization (Xu and AbouRizk 1999, Kamat and Martinez 2003, Peña-Mora et al. 2008). While great advances have been made in construction simulation over the past few decades, adoption by industry has lagged, for three potential reasons: simulation is not accessible, it cannot handle the complexity of modern construction projects, and the benefits are not immediately obvious.

2. Construction Synthetic Environments

Synthetic Environments provide the foundations for modeling techniques that enable: "a comprehensive representation of the natural environment; the ability to explore and visualize interactions and hence improve understanding of the 'real world'; a flexible and relatively low cost (compared to live trials or prototypes) way to explore issues and proposed solutions ahead of major investment and commitment; enhanced training opportunities, free from environmental constraints including interaction with other co-operating or opposing participants; and a through-life approach to applications." (UK Ministry of Defence 2005).

Motivated by the success of SEs in military applications, and the underlying goals of comprehensive modeling, the Research Team at the Hole School of Construction Engineering at the University of Alberta has pursued the development of a simulation framework based on the concepts of Synthetic Environments in an attempt to advance modeling and automation in construction practice (AbouRizk and Robinson Fayek 2006). The framework is referred to as COSYE (COnstruction SYnthetic Environment). One of the first findings of our research activity was that the High Level Architecture (HLA) is well suited for complex applications such as the ones we are dealing with. COSYE was, therefore, built using the HLA standards. It is capable of supporting building complex virtual environments (called federations) using distributed simulation technologies. In addition, it provides standards for building the individual components (federates) of such environments by different developers while maintaining interoperability, and facilitates the reuse of the developed components.

The HLA standards (IEEE 2000) consist of three main components: the HLA rules, the interface specifications, and the Object Model Template (OMT). HLA rules must be obeyed if a federate or federation is to be regarded as HLA-compliant. The interface specification defines the functional interfaces between federates and the run-time infrastructure (RTI). The RTI is software that conforms to the HLA specifications and provides software services such as synchronization, communication, and data exchange between federates to support an HLA-compliant simulation. Federates do not all need to be simulation models; instead, an HLA-compliant federate is any software that interfaces with the RTI as part of its standard services. The framework for CSE development has been in use for over three years now. It provides tools to define and build the federation object model (FOM) and compile it into .NET assemblies. Through this framework, developers can customize the abstract generic base federate to produce particular simulation behaviors and capture unique systems.

Further to our adoption of the HLA as a standard, the design philosophy of the COSYE API utilized, to the greatest extent possible, the visual nature of Microsoft's Visual Studio development environment. Therefore, our developments are applicable only to Windows based operating systems. COSYE is composed of a framework and the supporting tools (FOM, RTI, OMT), and it allows multiple teams to collaborate on developing models for the same project (for more information, please refer to (AbouRizk and Hague 2009)). Disperse groups at different locations can populate, interact with and run simulations of the project in whole or in part. This framework has been used to develop four synthetic environments which facilitate both planning and analysis of construction projects – large scale projects modeled in depth through COSYE and integrating multiple world-views of simulation – which demonstrate COSYE's breadth of application. The Industrial Construction Synthetic Environment, developed in collaboration with PCL Industrial Management Inc. (Taghaddos et al. 2011) models the supply chain of industrial construction, including the capture of all features, resources, and processes required to design, build, and maintain a facility. The Structural Steel Fabrication Synthetic Environment, developed in collaboration with Waiward Steel Fabricators Ltd. (Alvanchi et al. 2011) uses a hybrid of system dynamics and discrete event simulation to model the complexities of "soft" aspects of construction, (such as people skills, supervision) and integrating 3D CAD models and real time input into the simulation models to create enhanced reporting through earned value analysis. The Tunnel Construction Synthetic Environment models tunnel construction as a system and represents all facets from design to completion; it was developed in collaboration with the City of Edmonton (Moghani et al. 2011). Finally, and to demonstrate and explore the potential of COSYE in training, the Bidding Game environment, which simulates the process of bidding for construction projects and incorporates a fuzzy-logic-based virtual player, was created through a graduate course (AbouRizk et al. 2010).

3. Simphony

Along with the development of COSYE, Simphony, our process interaction simulation toolkit specifically for construction operations, has been advanced. Simphony allows rapid deployment of special purpose simulation tools or “templates” (for some recent examples, see Hong and AbouRizk 2011, Tian et al. 2010, Pan et al. 2010) and provides a user-friendly interface for construction end-users; it has been used to develop and deploy many solutions within academia and industry, including at PCL, Waiward, Graham, North American Construction Group, Standard General, KBR, City of Edmonton, SMA Consulting, and others.

To facilitate building process interaction models within COSYE, we have recently completed modifications to Simphony to enable it to be integrated within COSYE as a federate. In this manner, users can take advantage of the Simphony interface to rapidly create and modify simulations with no coding required, but those simulations can send and receive information to and from the COSYE environment. The tunnel simulation template and the land reclamation template have been fully integrated with COSYE for demonstration (Moghani et al. 2011). All other federations we referred to had their discrete event simulation federates built using programming code.

Simphony’s integration into COSYE is accomplished via an element called “RTI Connection,” which establishes communication with the RTI (described earlier) using .NET remoting via TCP/IP. The template developer controls what information is available or requested by a given template by making the elements “COSYE-aware”; the RTI Connection element handles time management and the communication with the RTI, which means that the model developed using the template, is the actual federate which joins the HLA federation. The RTI Connection element consists of two parts, the RTI Ambassador and the Federate Ambassador, which together handle connections to and from the RTI, respectively. Simphony is multithreaded, which means it is capable of executing instructions simultaneously. It has two default threads, one for the user interface and one for the simulation execution. In stand-alone operation, Simphony template elements generate events and place them in the event queue, which are then executed by the simulation thread. When Simphony is operating as part of a COSYE federation, the RTI Connection element’s Federate ambassador “listens” for communications from the RTI. When a communication from the RTI is received, a separate communication thread is created, which then generates a corresponding simulation event – scheduled either immediately or at some time in the future – and puts it in the simulation thread event queue. Simphony’s simulation engine is “thread-safe”; that is, written in such a way that it can be accessed by multiple threads simultaneously, which is what allows the communication thread to safely add events to the event queue. This design allows a Simphony model to be a full member of a federation and to take full advantage of the power of distributed simulation, while still remaining very easy to use.

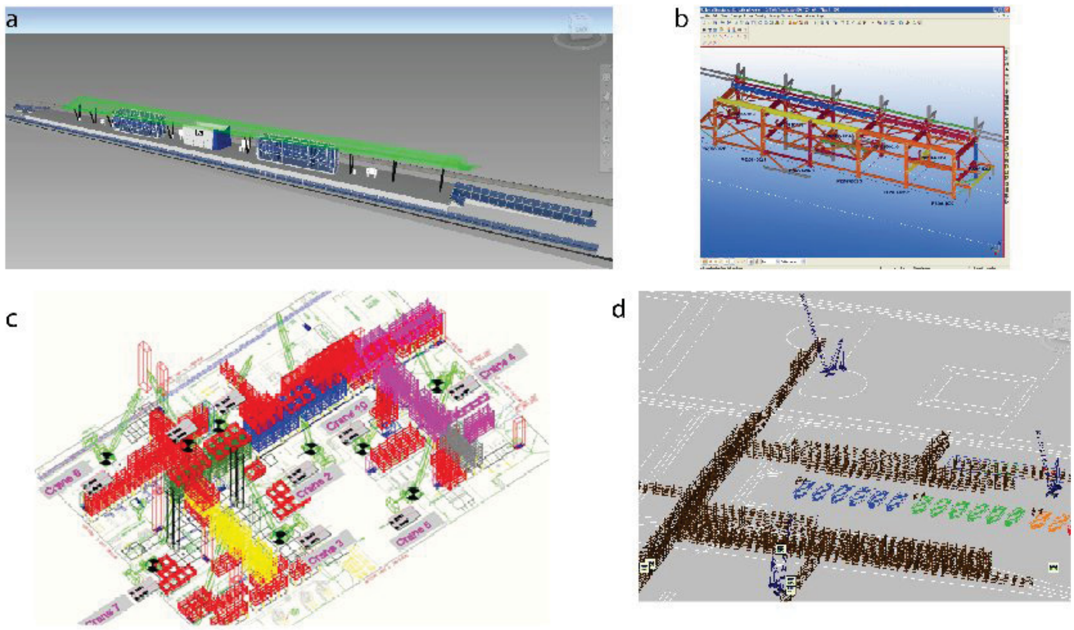

Fig. 1: 3D Visualization Models. Credit (d) H. Taghaddos, U. Hermann, PCL Industrial Management Inc.

4. 3D Modeling and Visualization

More and more, the construction industry is adopting 3D visualization as a tool for planning and building complex projects (Rekapalli et al. 2009, Wood and Alvarez 2005). 3D visualization, linked with simulation, is the answer to making the benefits of simulation accessible to industry practitioners. One major use for 3D visualization is interference checking, where multiple 3D models of different systems – a common example is multiple utility systems – are combined in 3D space, allowing the modeler to investigate potential conflicts. For example, Zhang et al. (2011) demonstrated the use of 3D CAD interference checking to determine whether there were utility conflicts in the construction of a subterranean light rail transit station in the City of Edmonton (Figure 1a).

Another use for 3D visualization is to demonstrate the process of construction itself, incorporating the element of time into a 3D CAD model. There has been great interest in 4D modeling, as it can assist in constructability review and be an enormous boon to planning. It is especially useful for very complex or curvilinear structures, such as the Beijing National Stadium (the "Bird's Nest"), erected for the 2008 Summer Olympics (Lu et al. 2009), and the Walt Disney Concert Hall in Los Angeles, completed in 2003 (Wood and Alvarez 2005). Zhang et al. (2011) also demonstrated its use in the planning stages of the North Edmonton Light Rail Transit system.

Once the time element has been incorporated into the 3D model, the opportunity exists for additional information to be integrated into the model and displayed via labels, color coding, overlays, etc. Recently, Azimi et al. (2010) demonstrated the use of so-called "5D" modeling to represent Earned Value Analysis on a steel fabrication project (Figure 1b), where steel pieces are colored according to their current status. This kind of information-rich visualization can bring together and display large amounts of data which would be difficult to grasp any other way. In a similar vein, Taghaddos et al. (2010) used 4D animation to convey the information generated by an integrated system for optimizing crane placement and the lift schedule during the construction of a heavy industrial project (Figure 1d). The user can see and easily understand the 4D project execution plan. El-Nimr and Mohamed (2011) are also exploring the use of 4D visualization of heavy industrial construction, but in a more tightly integrated fashion (Figure 1c).

To expand on the advancement summarized above, we explored integrating visualization dynamically into a simulation in such a manner where communications can be two ways (from the CAD model to simulation and the other way), where the CAD model can also influence simulation at run-time as well as diplay simulation progress in real-time. Through the distributed CSEs described earlier, it is possible to integrate independent 3D models into a federation, and to have them simply behave as federates. The software used to generate the 3D model can change depending on the preference of the modeler; for example, there have been visualization federates created using Tekla (Azimi et al. 2010), Blender (El-Nimr and Mohamed 2011), Microsoft XNA (Zhang et al. 2010), NavisWorks (Taghaddos et al. 2010) and Google Earth (Zhang et al. 2011), among others. Once a 3D model is integrated into a simulation, it becomes possible to explore new methods of interaction with that simulation. The models can be dynamic, and can both respond to and influence the simulation model itself. Visualizing unexpected events, like breakdowns, is problematic for traditional methods of 3D visualization, but dynamic, "real-time" (or simulation-time) visualization offers the opportunity to allow users to directly influence the simulation through the visualization. It can also be dynamically updated with real-time data collection, mediated through the simulation, such as RFID data (Azimi et al. 2010) or direct input from the project site (Xie et al. 2011).

5. Tunneling Federation

For this paper, the Tunneling CSE, developed in cooperation with the City of Edmonton, was chosen to illustrate the potentials for integrating simulation and 3D visualization using the COSYE framework. In this phase we attempted to model tunnel construction as a complete system. We also used on-going real life projects in the process in order to better understand complexities involved; in particular, the NEST tunnel, and the North LRT tunnel. A schematic illustration of the federation is given in Figure 2 for illustration.

The Tunnel federation incorporates a number of different federates that are independent built to model various aspects of the tunnel construction process. In this paper we focus on two federates: the visualization federate, which displays 3D visualization of the simulation, and the Simphony tunnel model federate, which handles the simulation itself. Additional federates can be added as the complexity of the model requires (for example, we are experimenting with a training federation to teach students about tunnel construction (Ekyalimpa et al. 2011). This is built as an extension to the current federation by simply adding more federates).

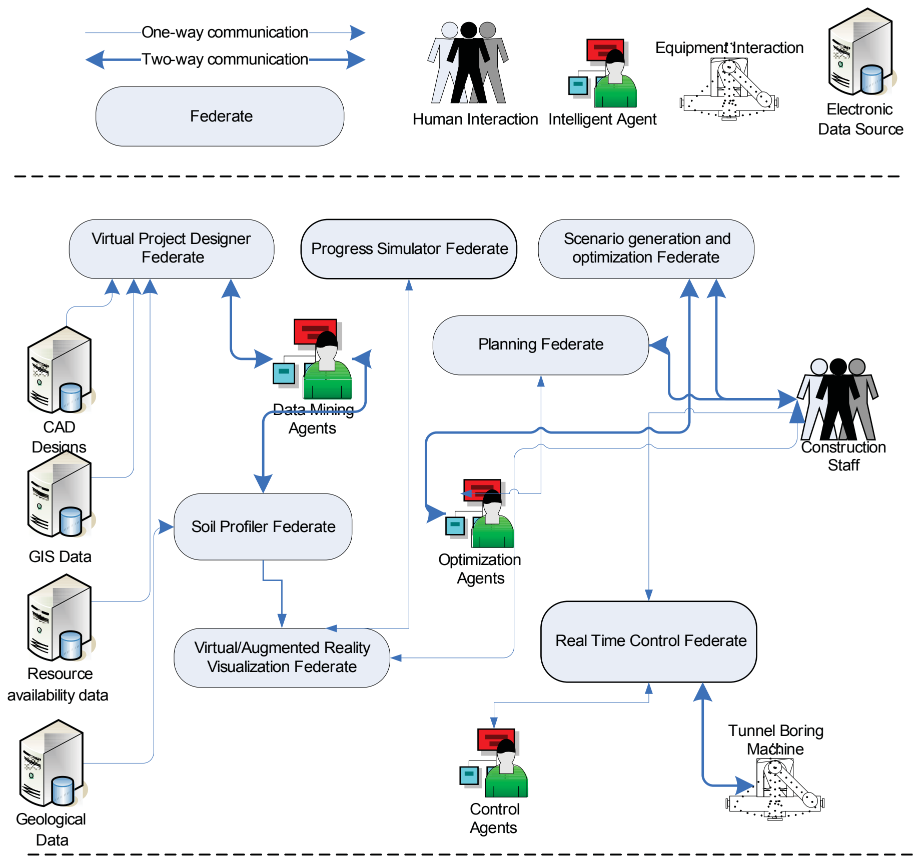

Figure 2. Conceptual model of the tunnel federation

5.1. Simphony Federate

The Simphony tunnel federate is hierarchically organized including sub-models for surface operations, shaft excavation, undercut excavation, TBM installation and setup, tunnel operation, equipment breakdown generation, and final liner installation (if required). The tunnel operation contains elements which the user assembles to simulate the advancement of the tunnel boring machine, the transportation of muck from the face of the tunnel to the undercut area for example. Fairly detailed models can be created using standard process interaction techniques and by simply using elements from a tunneling template. Furthermore, written code in C# or Visual Basic can be used to add additional features to the models or to change the behavior of various elements

A simulation model of a tunneling project was created in Simphony using the Tunneling template (Figure 3, left) to demonstrate the visualization capabilities. The tunnel project which is simulated here is a drainage tunnel project located in Edmonton, Alberta, Canada. The proposed tunnel is associated with the portal for the underground section of the Edmonton North Light Rail Transit (NLRT) extension. The drainage tunnel has an inside diameter of 2340 mm, and an approximate length of 500 m. Based on design documents, a working shaft and retrieval shaft will be located at each end of the proposed drainage tunnel. For the tunnel construction, a shielded TBM with a diameter of 2540mm is utilized for the excavation and lining process. In this method, a tunneling cycle starts with the excavation process; the TBM excavates the whole section of the tunnel and advances approximately one meter by jacking against the installed liners. Then it is used to place precast concrete segments and line the excavated area. After the liner installation, the TBM jacks are reset to the new position. This will continue until the end of the tunnel. Different activities such as surveying, extending utilities or tracks are usually scheduled on a certain time intervals.

The working shaft is used to lower down the material and equipment and removing dirt from the excavation process. A train of muck carts and a material cart is used to transfer dirt from tunnel face to the working shaft and to bring liners to the TBM. The retrieval shaft is constructed to remove the TBM at the end of the tunnel. In this construction method, the larger area should be excavated at the bottom of the shaft and before the start point of the tunnel. This area, called the undercut, facilitates the process of lowering down the TBM and positioning it at the start of the tunnel. Also, to facilitate train movement at the bottom of the working shaft for loading liners and unloading the dirt, a tail tunnel is constructed at the bottom of the working shaft.

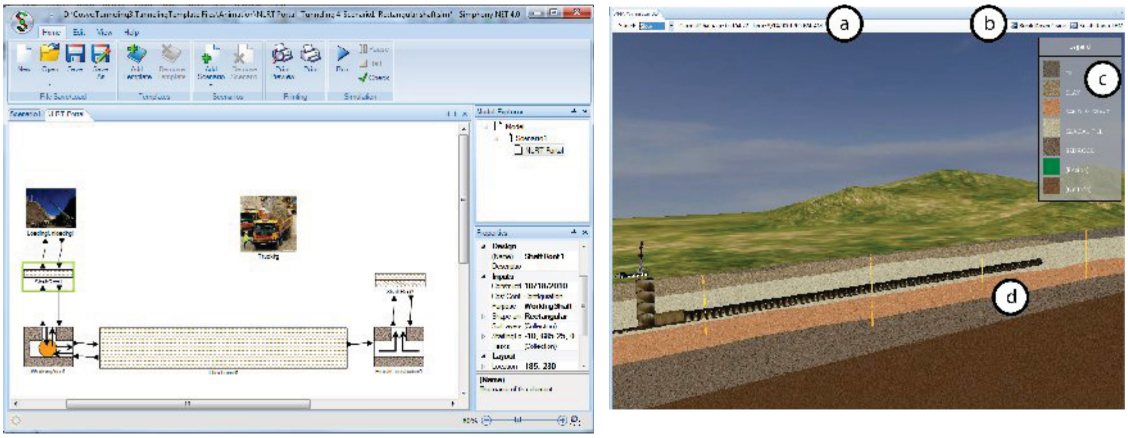

Figure 3. Simphony.NET 4.0 tunneling model (left) and 3D visualization features (right)

5.2 The 3D visualization federate

The visualization federate (Figure 3, right) was built using the Microsoft XNA game engine, which is a framework and set of tools which facilitate the creation of animated 3D environments. The federate loads a 3D model of the geotechnical conditions through which the tunnel passes (from design drawings); the soil layers are differently textured, and a legend is provided; the boreholes are represented via yellow crosshatched rectangles (on the figure). A "skybox" (essentially an animated backdrop which displays distant landscape features and moving clouds, and changes with the time of day) and a textured landscape provide realism. The federate has a library of 3D models (i.e., the TBM, the crane, the tunnel segments) and textures which it resizes and uses to build the tunnel model, based on the information which is generated by the simulation. The TBM's movement is controlled by the current chainage, provided by the simulation during run-time. During visualization, the speed of simulation can be controlled through the visualization federate (i.e., the simulation normally is slowed down to the speed of the animation), and the point of view can be controlled either through the keyboard or via a Microsoft Xbox 360™ controller for Windows. Stochastic events such as a TBM breakdown or a crane breakdown can be initiated through the simulation or through the visualization federate. In either case they are reflected in both (and other federates) in a synchronized manner. In Figure 3 (right), the interface is shown; the user can set the simulation speed and view the current chainage and time (a), break down the crane or TBM (b), and see the geotechnical information (c, d).

5.3 Scenario planning using the federation

Four scenarios (Figure 4) for the construction process were defined for the NEST tunnel. The original plan (see Figure 3, right) was to use a circular working shaft with a depth of 13.5 m and a circular removal shaft at the same depth. A shielded TBM with a diameter of 2540mm was used to excavate a 496 m tunnel. Two muck carts with a capacity of 3 m3 were used to remove soil from the tunnel face. Scenario 1 is the replacement of circular working shaft, undercut, and tail tunnel with the rectangular shaft which has bigger dimensions. The rectangular shaft is an open pit that gives more area for lowering down the TBM and moving muck carts during the construction period. The proposed change eliminates the process of excavation and lining of undercut and tail tunnel in a separate stage than constructing the shaft. In Scenario 2, the number of muck carts for removing dirt was increased. In the original plan, two muck carts with the capacity of 3 m3 were considered. The total excavation dirt volume can be more than 6 cubic meter if the soil changes along the tunnel alignment. So, in this scenario we increase the number of muck carts to 3 at 2.5 m3 each, to make sure that their capacity will be enough even for different types of soil with a larger swell factor. In Scenario 3, an existing TBM with a different diameter, 3.2 m, was chosen for excavation purposes. By selecting this option the number of muck cart were increased to 4 with the capacity of 3 m3 each. In Scenario 4,,the tunnel inverted elevation was changed to move the tunnel to a lower soil layer. This change will affect the TBM advancement because of the changes in the soil property. By moving the tunnel to the lower elevation the depths of the working and removal shafts are increased respectively (from 13.5 m to 20 m). This increases the cost and duration of shaft construction, but on the other hand decreases the duration of the tunnel construction.

These scenarios can be quickly and easily demonstrated using the visualization federate with no further 3D modeling involved (Figure 4); all options are set from the Simphony interface. The user can also explore the effects of breaking down the TBM or the crane. The results of 100 runs of the simulation can be seen in Table 1. Scenario 4 is the least expensive and has the earliest project completion time, as a result of the favorable properties of the lower soil layer.

Table 1. Results of simulation for the original and alternate scenarios.

Scenario	Depth	TBM size	Muck carts	Shaft shape	Cost	Finish Time
Original	13.5 m	2.5 m	2	Circular	4,469,590	November 14, 2011
Scenario 1	13.5 m	2.5 m	2	Rectangular	4,412,280	November 9, 2011
Scenario 2	13.5 m	2.5 m	3	Circular	4,270,760	November 23, 2011
Scenario 3	13.5 m	3.2 m	4	Circular	5,405,510	March 20, 2012
Scenario 4	**20 m**	**2.5 m**	**2**	**Circular**	**3,903,580**	**October 13, 2011**

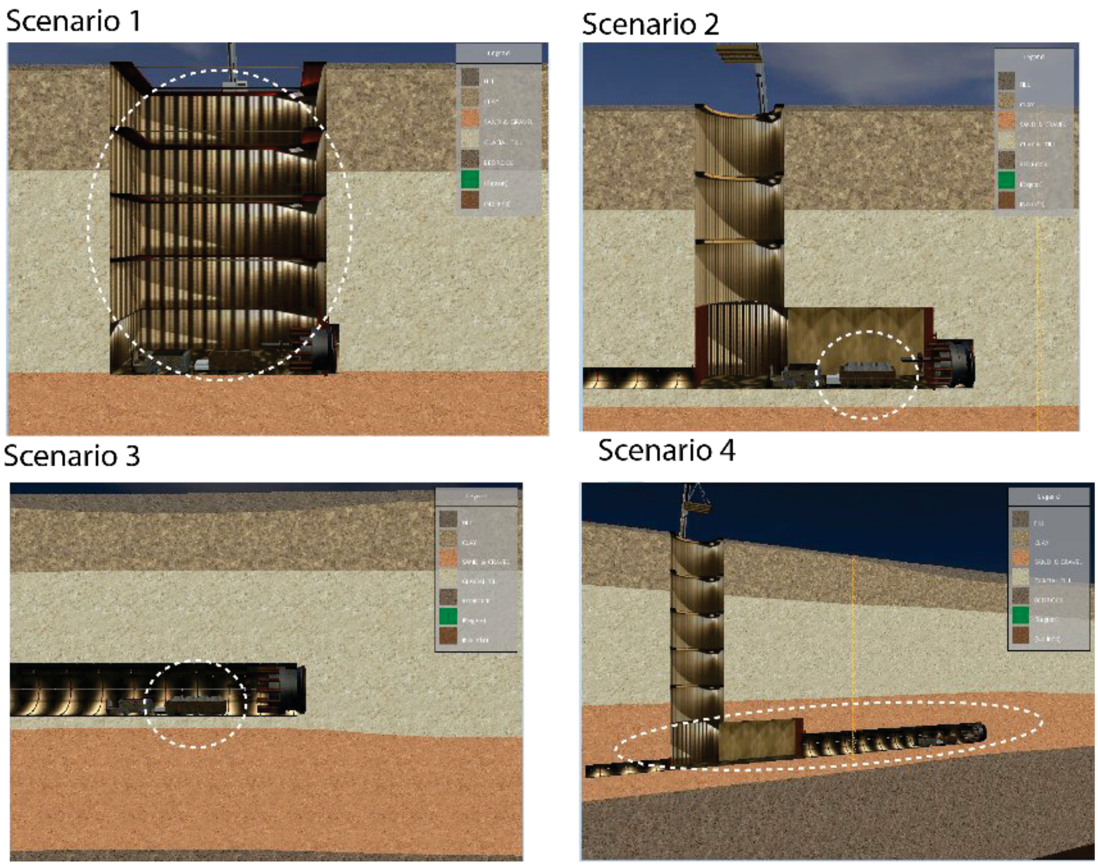

Figure 4. Tunneling visualization. Dotted circles indicate areas of interest.

6. Conclusion

The synthetic environments approach to modeling offers significant potential for improving modeling and analysis in construction projects. Using the HLA standard for distributed simulation, and building on previous research works within construction we successfully built a development framework (COSYE) which represents the foundation for building large scale, complex, dynamic simulation in a collaborative fashion and for distributed applications.

Through the CSE environments, we have developed techniques for providing a comprehensive approach to modeling and simulation whereby the product, the process, the environment and the interacting players are seamlessly involved within the simulation. The approach proved useful in integrating 3D models within simulation environments while resolving many issues related to the dynamic interactions between such models and simulation. It also proved useful in facilitating the deployment of: (1) techniques for automated data acquisition from construction operations including through RFID (Azimi et al. 2010), web based forms (Moghani et al. 2010), external databases and financial systems (proprietary; in collaboration with Waiward Steel Fabricators Ltd. and Standard General), and barcoded infrastructure; (2) advanced control methods using Bayesian updating techniques, data mining approaches (Xie et al. 2011), etc., with corresponding 4D and 5D models (in collaboration with Waiward Steel Fabricators Ltd., the City of Edmonton, and PCL Industrial Management Inc.), and (3) sensing (RFID and Wifi) and automated data acquisition applications for safety in tunnel construction.

These developments create a rich environment in which we can advance the project delivery process to one where processes composing the construction supply chain are "fully integrated and highly automated, and where advanced technologies are utilized across all project and facility life cycles" (FIATECH 2009).

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PAPERS

CONSTRUCTION PROCESS INTEGRATION (CPI) BASED ON MULTI MODEL DESIGN

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ABSTRACT: *This lecture will show actual status and outlook of integrated construction processes based on Building Information Modeling (BIM) from different design teams. These so called 5D processes have been approved in 2011 on several project types at contractors like Haley's (UK), UGL (Australia), Max Bögl, Züblin and Wolff + Mueller (Germany). For the main part of the execution real world 5D projects will be referenced. In addition future technology will be considered with new kinds of model types e.g. for allowance activities. The different process steps will be explained with the used terminology and technology for typical 5D implementations. Starting with model based estimating and tendering the needed team, data and IT structure will be shown. One focus is the Quantity Take Off (QTO) and the Project Planning (PP) workflow, both using company and region standard rules like Standard Methods of Measurement (SMM) applied to the BIM data from Multi Model Design (MMD). Detailing of data structure in the construction preparation will be followed by the model based allowance and project control with interfaces to classical finance processes e.g. in Enterprise Resource Process (ERP) software like SAP including Earned Value Method (EVM). These kind of full 5D integration allows the visual simulation of project progress as planned, as actual and as forecasted.*

KEYWORDS: *CONSTRUCTION, BIM, QTO, 5D, PROCESS INTEGRATION, MULTI MODEL DESIGN, EVM*

1. Introduction

Thanks to new IT technologies like used in automotive (fig.1) or game industry (fig. 3) the vision of data and function integration during the full construction process becomes more and more reality. Based on multiple individual interacting data models created by different experts, a BIM (Building Information Modeling, fig.4) structure allows controlling all steps in design, work preparation and calculation of Multi Model Design (MMD). Today many contractors already use model based estimation to visualize the resource planning for the internal and external communication. Combined with a work schedule simulations in 4D (geometry+ time) and 5D (+ resources) can help do understand the technical and cash workflow of complex buildings and infrastructure projects.

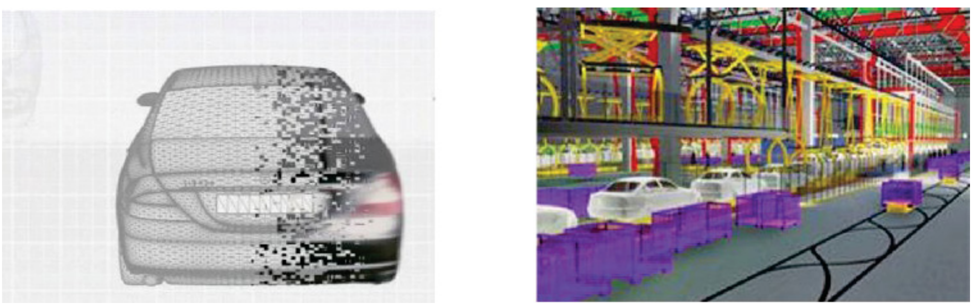

Fig. 1: Digital product and factory design (source: Mercedes Benz)

1.1 Process overview

Implementation of construction data integration has to recognize all needed process steps using BIM during the project lifecycle (fig. 2). Already in the setup starting with project structures and part models unique identifiers of all data sets are necessary for communication of all IT components in later usage. Before starting with quantity survey and cost estimation the design from the expert models has to be consolidated. Often in this phase many detail conflicts between the expert models can be detected.

A rough project timeframe of the construction workflow makes sense before budgeting and tendering process for a first 5D estimating model. Step by step based on closed contracts with clients and (sub-) contractors the site preparation can be done with a more and more detailed scheduling and work breakdown structure. Later the procurement of on side services, material and equipment uses the same data model as the validation, invoicing, payment and project control functionality.

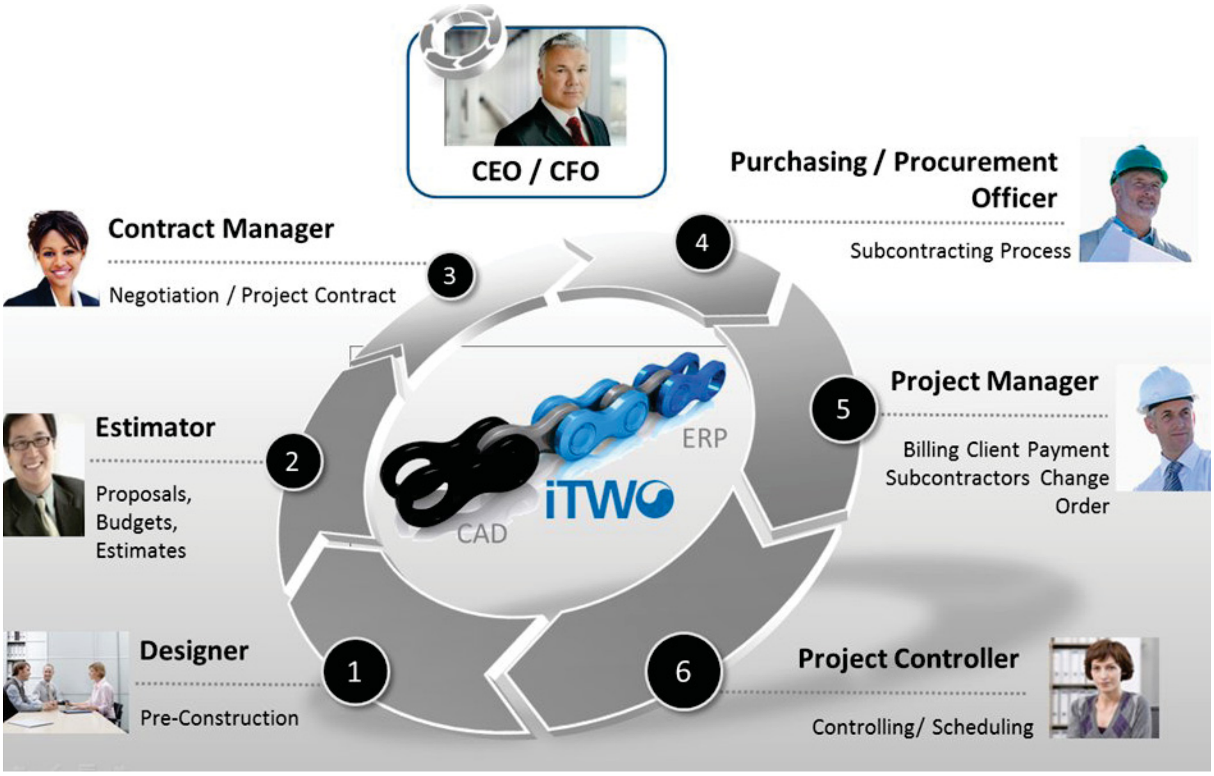

Fig. 2: Roles in an integrated construction process (source: RIB AG)

1.2 Available software and technology

Five types of standard software (Office; CAD; Estimation; Scheduling; Finance) are in use in most construction processes. Today most shareholders use office products like Excel and Word combined with printouts, emails and file servers as base for the communication between the project partners. Design data is generated as PDF or printouts from CAD systems like AutoCAD or Microstation. In addition bill of quantities (BoQ) or work breakdown structures (WBS) are calculated with local estimating tools like WinEst or Arriba. For accounting and payment each project partner uses individual finance software. When integrating these tools into a common construction data process companies can choose between a bunch of individual interfaces, partly integrated solutions like REVIT in design coordination, or fully integrated databases like RIB iTWO in project coordination and SAP in financial coordination. Powerful integrated software systems are based on databases with relational and/or object oriented technology. These systems allow multiuser operation in an application server environment, allowing access to functions and data sets based on roles (fig.2), secured by personal logins.

To access and view complex geometric data powerful graphic engines are needed, coming from mechanical CAD (fig.3) or computer game industry (fig.4) with OpenGL or DirectX standard. The geometric information from multiple part models can be consolidated together with object data and structure in BIM related formats like IFC and/or CPIXML.

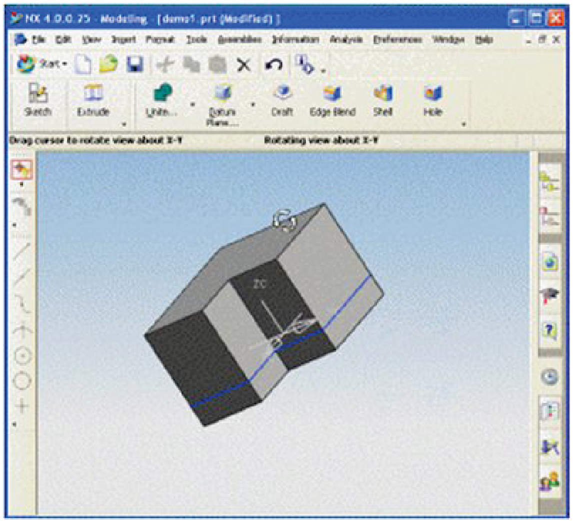

Fig. 3: Siemens NX parametric CAD (source: Siemens)

Fig. 4: SimCity game (source: Electronic Arts)

Cloud technology allows distributing functionality and data sets in different physical location around the world without losing the integration of workflows and common model structure. RIB iTWO combines this integrated but distributed software system with interfaces to local standard tools. This allows the creation of 5D simulation and project control on base of standard data from several 3D CAD, estimating and scheduling sources in one dynamic project model for all shareholders.

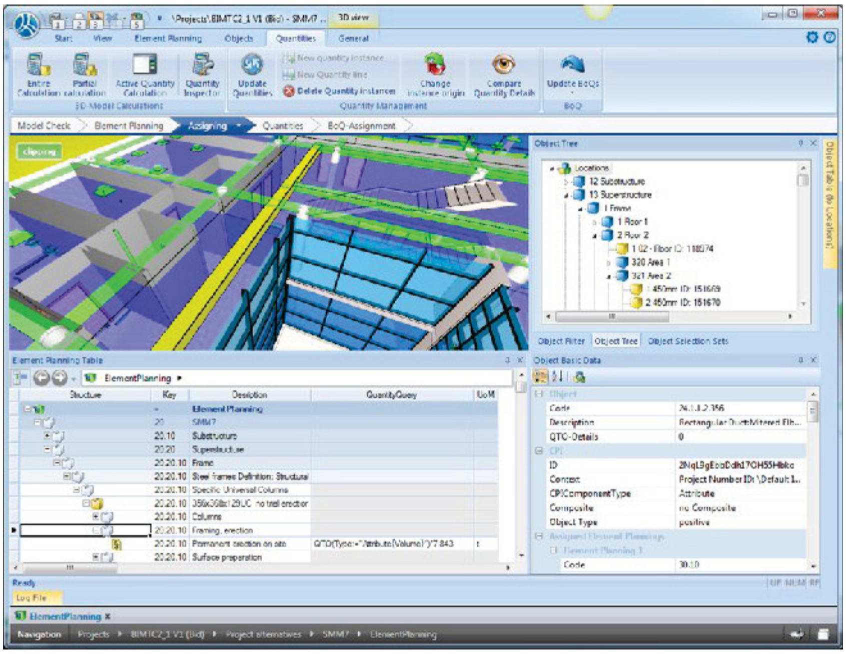

Fig. 5: Multi Model Design consolidation from different CAD sources (source: RIB AG)

2. Model based estimating and tendering process

In a model based process the quality of estimating and tendering data is dependent on the delivered expert design models from architects and different engineers. Therefor each estimating process should begin with the coordination and integrity check of the delivered CAD / BIM data (fig.5). Functions like clash detection and model integrity check can help to avoid many problems later in the project progress.

Parallel to the model consolidation appropriate standards and catalogues are chosen for the Bill of Quantity (BoQ) and Work Breakdown Structure (WBS). Step by step they will be enhanced by project specific details. Systems like RIB iTWO allow dynamic assignment of these structures to the BIM data based on geometry and attribute information. These assignments can be done manually in a 3D viewer by a Quantity Surveyor (QS) or automatically generated by computer rules based on local QTO (Quantity Take Off) standards like SMM or VOB (fig.6). As legal rules do not calculate the really needed resources, additional QTO rules will be applied for the company specific calculation assemblies. The detailing of the quantities is dependent on the phase of the project (rough estimate, work preparation, project control).

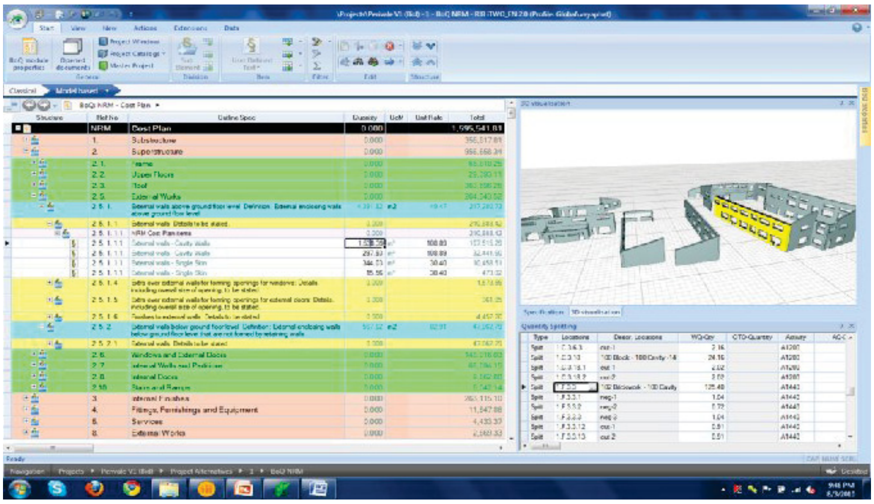

Fig. 6: Model based Bill Of Quantities according SMM7 (source: RIB AG)

When packaging the work items for (sub-) contracting, the data of the sub packages has to stay connected to the whole project model by unique IDs. Beside quality details the electronic transfer of data between the shareholders can now also contain quantity details connected to geometric BIM data. For general and subcontractors these part models allow exact calculation of prices including project specific allocations of general expenses, risks and profits.

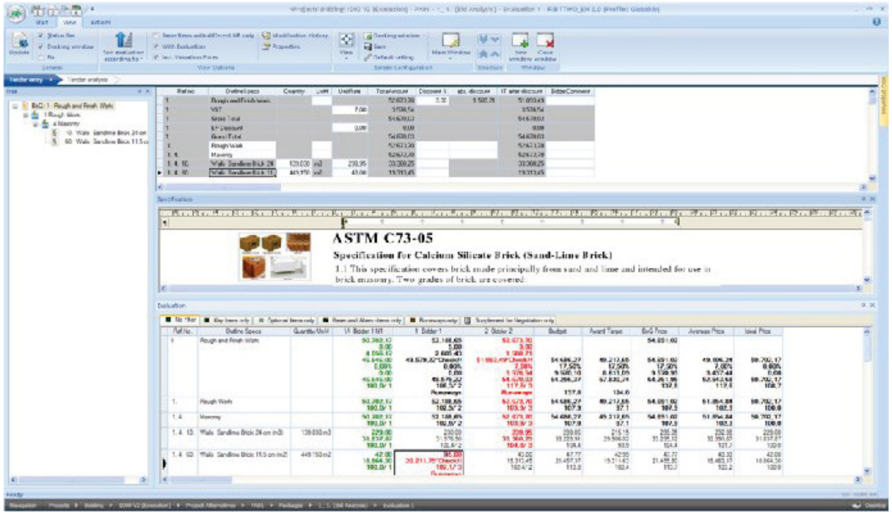

Fig. 7: Supply chain management with model based resources (source: RIB AG)

3. Model based work preparation process

In automotive industry “lean production” combined with “delivery on time” since several years performs fast standard processes combined with individual detail design (fig. 1). Model based integration with all shareholders allows the adaption of these methods to the construction industry. Today contractors like Max Bögl combine BIM construction modelers like REVIT and TEKLA with project systems like iTWO and ERP systems like SAP for a construction process which can be compared with any automotive lean production. If all partners are involved, work preparation can plan the whole production of the building or infrastructure product by calculating the labor, material and equipment exactly for the right time at the right place. A 5D simulation (fig.8) based on an overall production site model allows easy communication of these processes between all shareholders. Changes before and during the construction phase can be agreed before legal conflicts may occur.

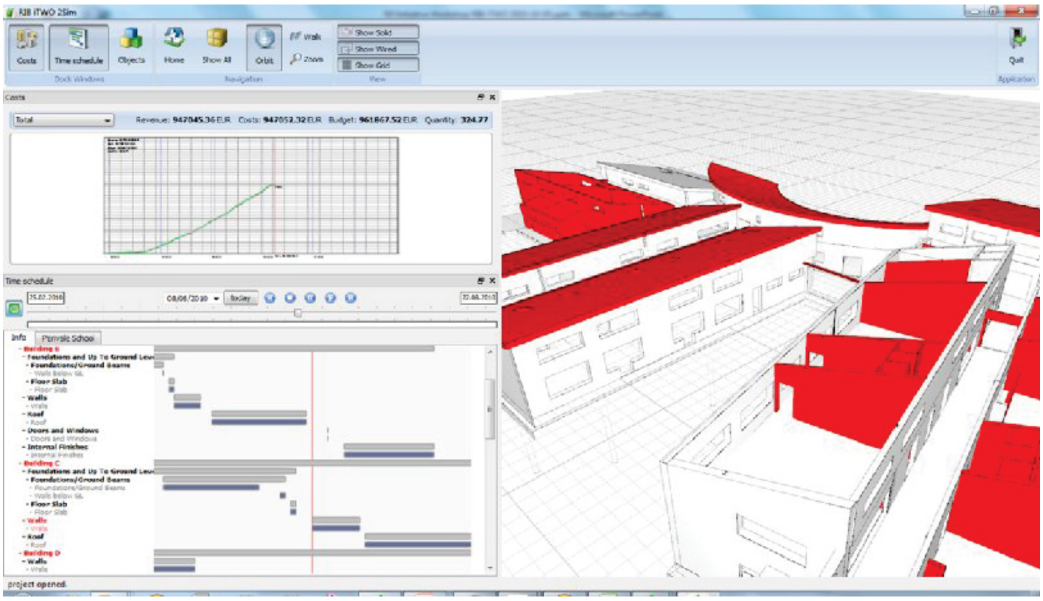

Fig. 8: 5D Simulation with cost chart, project schedule and 3D progress viewer (Source: RIB AG)

4. Model based allowance and control process

Last but not least cash flow analysis, cost control and forecasting can be integrated in the model based processes. Budgets are based on the planned resources, structured in locations and schedules from the 5D model. Allowances of payments and invoices are dependent on the technical actuals compared with the budgeted plans. RFID (Radio-frequency identification), GPS/WLAN, laser and 3D photo technology allow tracking of the supply chain and production progress.

The earned value method (EVM) combines the schedule performance ("As build" compared to "Planned") with the cost performance ("As Accounted" compared with "As Budgeted"), each from the same 5D data model including all planned and actual technical and finance information (fig.10).

Fig.9: Control and reporting of "As Build" data by on side GPS / WLAN technology (source: TOPCON, RIB AG)

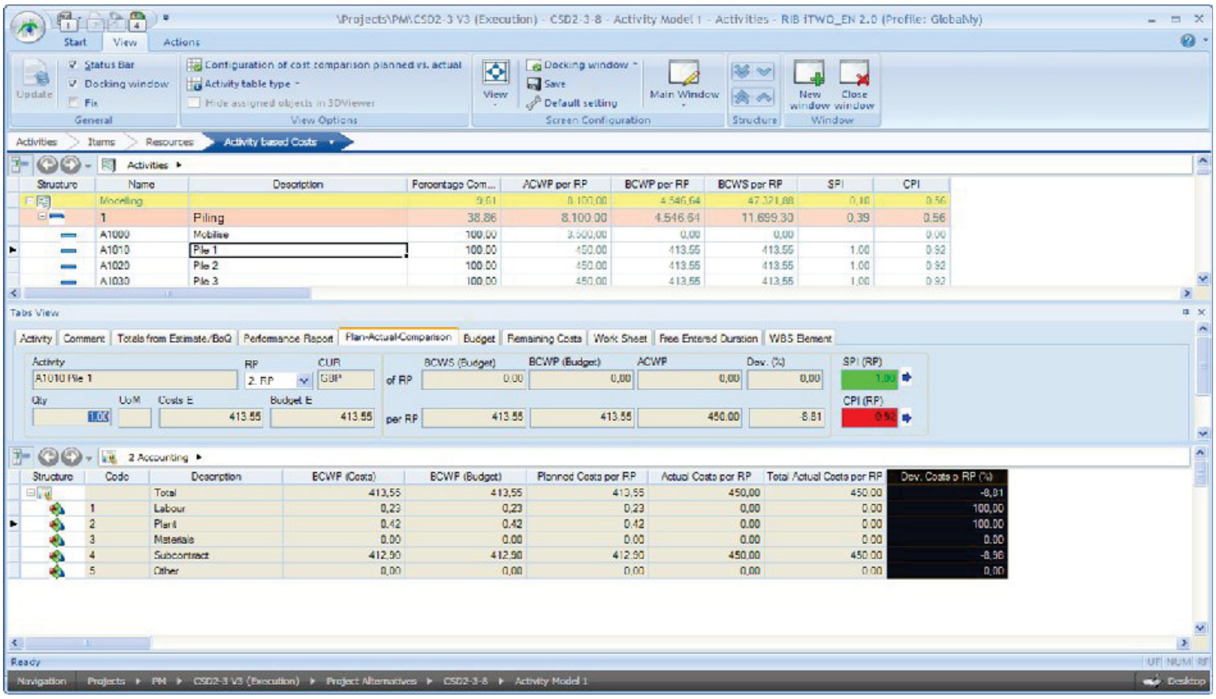

Fig. 10: Progressive job cost control by Earned Value Method (source: RIB AG)

IT providers like SAP and RIB together deliver such integrated industry solutions to international contractors (fig. 11). It should be only a matter of time, when more and more other shareholders including investors, engineers and small size subcontractors will become part of these upcoming 5D lean construction processes.

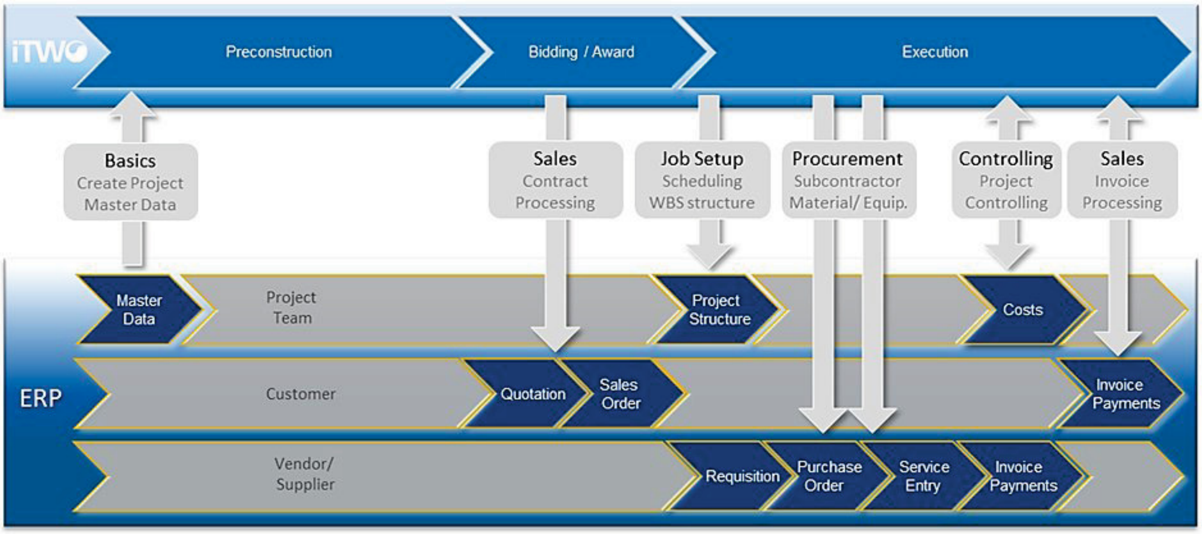

Fig. 11: Integration of Project Management and Enterprise Resource Processes (source: SAP, RIB AG)

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NUMERICAL SIMULATION AND VISUALIZATION FOR BUILDING ENVELOPE THERMAL DISTRIBUTION ANALYSIS

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ABSTRACT: *Over the past decade, growing concerns regarding global warming and energy supply problems have raised social awareness of energy conservation and carbon reduction, leading to green buildings emerging as a growing trend in building design and engineering. There are four main strategic areas for developing energy-saving buildings: (i) building envelopes, (ii) heating, ventilation and air-conditioning (HVAC), (iii) lighting and (iv) equipment. Among these, building envelopes have played the most significant role. If energy-saving strategies are considered when designing a building, low energy consumption and carbon dioxide emissions of the building can be expected. For example, reduced use of HVAC and lighting equipment can be achieved by simply considering the interaction between the building envelope and the surrounding environment, such as ventilation, sunshade, and ambient lighting. In this research, we focus on the thermal distribution of the building envelope. This research also develops a visual simulation system carried out in the MicroStation Visual Basic for Applications (MVBA) environment. The proposed numerical model was implemented in the visual simulation system for assisting planners in calculating the thermal distribution of the building envelope. This system provides a visual environment for presenting analyzed data and visualization models, and also assists planners in finding and utilizing relevant and necessary data in a more direct and efficient manner to achieve a good energy-saving design in the early stages of any building project, or to validate the final product design.*

KEYWORDS: *Numerical Simulation, Visualization, Solar Radiation, Thermal Distribution, Building Envelope*

1. Introduction

Currently, global warming and energy supply are set to be important issues in our lives, which is why many researchers have become more concerned about the concept of green buildings, sustainable buildings and low-energy houses [Satterfield, 2009; Karlsson et al., 2006], with green buildings emerging as a growing trend in building design and engineering. The concept of a “green building” is primarily driven by the objective of fully harnessing available resources to reduce pollution, creating the best possible environment with the least resources [Chang et al., 2011]. In the past, air-conditioning design-calculation focused on the estimation of peak loads which were determined either by manual calculation or simple computing methods. Nowadays, load calculation has not only become more complicated but there are also requirements to conduct energy analysis at the building’s design stage [Hui et al., 1998]. However, the heat exchange process in buildings is an unsteady state and consequently varies in time. Volatility of the heat exchange process is influenced by oscillating external temperature, internal heat gains, solar radiation and other factors that affect the heat balance of a building [Pupeikis et al., 2010]. Because solar radiation is a major contributor to the heat gain of a building, accurate estimation of solar radiation on the envelope of a building is required in many applications. For example, higher solar radiation received implies greater total solar heat gain and hence higher energy requirements for cooling. In designing an air conditioning system, knowledge of the total radiation striking a surface over a specified period of time is required [ASHRAE, 2009]. There are many ways to predict solar radiation [Bird et al., 1981; ASHRAE, 2009]. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) proposed a clear-sky radiation model to calculate the solar radiation on building surfaces. To design an air conditioning system, the equipment is sized for operation when the building is subjected to high solar radiation. A clear sky allows a high level of solar radiation to reach the earth and the ASHRAE uses a clear sky model for estimating the hourly irradiation on the earth's surface [Wessapan et al., 2008]. In this research, we focused on how solar radiation influences the thermal distribution of the building envelope, because solar radiation is the main influence on the thermal balance of a building. By analyzing thermal situations and improving them at the design stage, much energy can be saved because the requirements on cooling equipment can be reduced. To achieve this, this research developed a visual thermal distribution simulation system for analyzing and visualizing solar radiation of a building envelope. All of the application functions were implemented on the Bentley MicroStation. This system assists planners in identifying and understanding the possible blind spots affecting the achievement of energy-saving requirements of the designed buildings, and enables further design modifications to optimize energy-saving effects.

2. Proposed Methodology

With a global revolution in process towards the creation of a greener environment, there is increasing impetus to avoid energy waste and reduce carbon emissions. Solar radiation is responsible for most of the heat gain of a building. In this study, we developed a visual simulation system which can assist planners to calculate the thermal distribution of a building envelope. Figure 1 shows the flowchart of the proposed methodology for analyzing the solar radiation on a building envelope. The four step sequence presented in the flowchart is an important aspect of this study. Before analysis of solar radiation, the 3D model and numerical model should be ready for analysis and visualization. The new ASHRAE clear-sky radiation sky model of 2009 has three criteria during the selection and development process: accuracy, universality, and ease of use [Thevenard, 2009]. Firstly, a planner needs to specify the building envelope and define the grid size in the grid generation module. The grids will be generated according these settings for accurate calculation of thermal distribution on the surface. Secondly, the system will calculate the value of solar radiation using the numerical equation of the ASHRAE clear-sky model. In this research, the ASHRAE clear-sky model is used to estimate the monthly solar radiation on different slopes of different surfaces. However, different areas have their local climate characteristics and parameters. For accurate determination of solar radiation values, the latitude and longitude, local time-zone and local parameters of the building are needed for input into the model. To use the model at other locations to calculate the solar radiation values, it is necessary to adjust the atmospheric extinction coefficient and the diffuse radiation factor of the local sky, known as the model parameters, because of their local sky conditions [Wessapan et al. 2008]. Therefore, the database is also used for collecting climate parameters and area data in different regions. The system calculates the beam (Et,b), diffuse (Et,d) and ground-reflected (Et,r) solar radiation components of each grid surface. Following this, the system will analyze the total solar radiation received on the surface of the building envelope. Finally, the system will apply color schema to visualize the result of solar radiation calculations. A good visual representation of data can assist people in efficiently acquiring applicable information. Therefore, planners will be able to better understand the status of thermal distribution of the building envelope from this system, and then proceed to redesign or improve building design to achieve an effective energy-saving building.

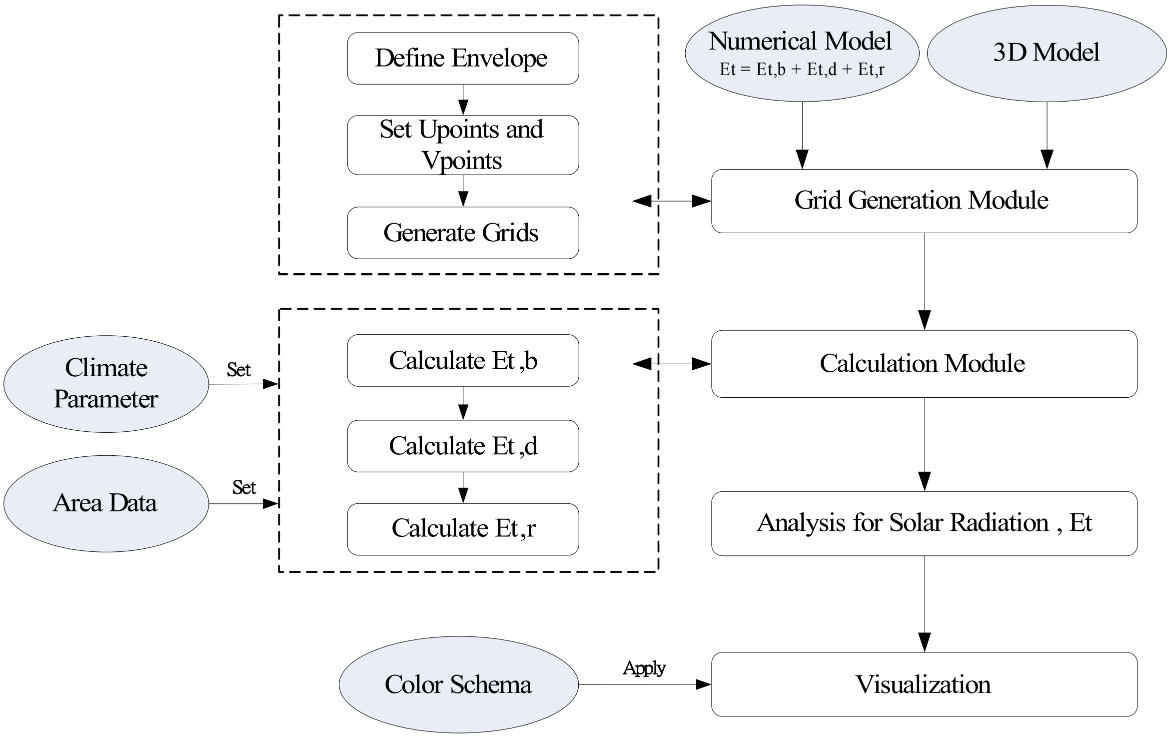


Fig. 1: The flowchart of the proposed methodology.

3. Numerical Model

In order to design an energy-saving building, we need to know the incident solar radiation on an envelope of the building. This is because solar radiation is a major factor for a building's heat gain. When the sky is clear, the building's heat gain is mainly from solar radiation. And we know the ASHRAE has a clear-sky model for estimating the solar radiations on a clear day. McQuiston et al. commented that the ASHRAE clear-sky model is commonly used as a basic tool for solar heat load calculation of air conditioning systems and building designs [McQuiston et al. 2010]. Therefore, we employed ASHRAE clear-sky model to calculate solar radiation of building envelope in this research.

Clear-Sky Radiation Model

Solar radiation is a major contributor to the heat gain of a building. As shown in equation (1), the total clear-sky irradiance Et reaching the receiving surface is the sum of three components: the beam component Et,b originating from the solar disc; the diffuse component Et,d, originating from the sky dome; and the ground-reflected component Et,r originating from the ground in front of the receiving surface [ASHRAE, 2009].

$$Et = Et,b + Et,d + Et,r \quad (1)$$

Air Mass

The relative air mass m is the ratio of the mass of atmosphere in the actual earth/sun path to the mass that would exist if the sun were directly overhead. This is represented by

$$m = 1/ [\sin \beta + 0.50572(6.07995 + \beta)^{-1.6364}] \quad (2)$$

where β is expressed in degrees.

Clear-Sky Solar Radiation

Solar radiation on a clear day is defined by its beam (direct) and diffuse components. The direct component represents the part of solar radiation emanating directly from the solar disc, whereas the diffuse component accounts for radiation emanating from the rest of the sky. These two components are calculated as

$$E_b = E_o \exp[-\tau_b m^{ab}] \quad (3)$$

$$E_d = E_o \exp[-\tau_d m^{ad}] \quad (4)$$

where: Eb = beam normal irradiance (measured perpendicularly to rays of the sun), Ed = diffuse horizontal irradiance (measured on horizontal surface), Eo = extraterrestrial normal irradiance, m = air mass, τ_b and τ_d = beam and diffuse optical depths, ab and ad = beam and diffuse air mass exponents.

Air mass exponents ab and ad are correlated to τ_b and τ_d through the following empirical relationships:

$$ab = 1.219 - 0.043\tau_b - 0.151\tau_d - 0.204\tau_b\tau_d \quad (5)$$

$$ad = 0.202 - 0.852\tau_b - 0.007\tau_d - 0.357\tau_b\tau_d \quad (6)$$

Beam component, Et,b

The beam component is obtained from a straightforward geometric relationship:

$$E_{t,b} = E_b \cos\theta \quad (7)$$

where θ is the angle of incidence. This relationship is valid when $\cos\theta > 0$; otherwise, $E_{t,b} = 0$.

Eb= beam normal irradiance (measured perpendicularly to rays of the sun)

Diffuse Component, Et,d

The diffuse component is more difficult to estimate because of the non-isotropic nature of diffuse radiation: some parts of the sky, such as the circumsolar disc or the horizon, tend to be brighter than the rest of the sky, which makes the development of a simplified model challenging. For vertical surfaces, Stephenson (1965) and Threlkeld (1963) showed that the ratio Y of clear-sky diffuse irradiance on a vertical surface to clear-sky diffuse irradiance on the horizontal is a simple function of the angle of incidence:

$$E_{t,d} = E_d Y \quad (8)$$

with $$Y = \max(0.45,\ 0.55 + 0.437\cos\theta + 0.313\cos^2\theta) \quad (9)$$

For a non-vertical surface with slope Σ, the following simplified relationships are sufficient for most applications described in this volume:

$$E_{t,d} = E_d(Y\sin\Sigma + \cos\Sigma) \text{ if } \Sigma < 90° \quad (10)$$

$$E_{t,d} = E_d Y \sin\Sigma \text{ if } \Sigma > 90° \quad (11)$$

where Y is calculated for a vertical surface having the same azimuth as the receiving surface considered.

Ground-Reflected Component, Et,r

Ground-reflected irradiance for surfaces of all orientations is given by

$$E_{t,r} = (E_b \sin\beta + E_d)\rho_g(1 - \cos\Sigma)/2 \quad (12)$$

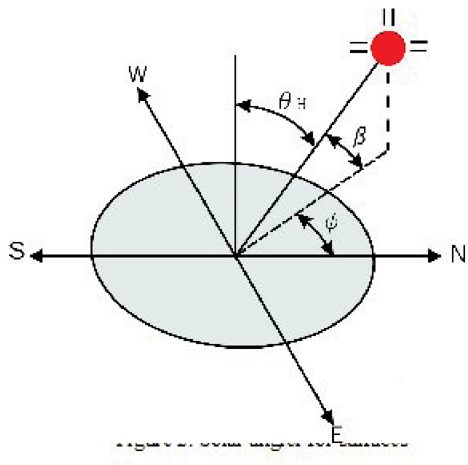


Fig. 2: Solar angler for surfaces

where ρg is ground reflectance, often taken to be 0.2 for a typical mixture of ground surfaces.

Example

In Kaohsiung city (Southern of Taiwan), direct, diffuse and ground-reflected components of solar irradiance are calculated on July 21 at noon, solar time. We assume that the azimuth of the receiving surface is 60°, θ=88.886°. Table 1 provides astronomical data for the calculation.

$$E_{t,b} = E_b \cos\theta = 15.534$$

$$E_{t,d} = E_d Y = 97.755$$

$$E_{t,r} = (E_b \sin\beta + E_d)\rho_g(1 - \cos\Sigma)/2 = 97.339$$

$$E_t = E_{t,b} + E_{t,d} + E_{t,r} = 15.519 + 97.893 + 97.276 = 210.628$$

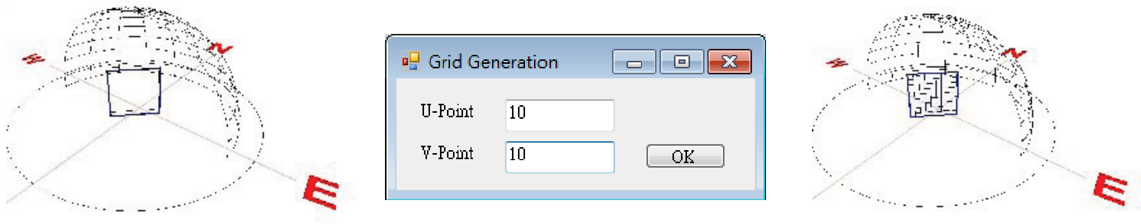
Table 1: Astronomical data for Kaohsiung city

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
E_o,w/m^2	1410	1397	1378	1354	1334	1323	1324	1336	1357	1380	1400	1411
Declination(δ)	-20.1	-11.2	-0.4	11.6	20.1	23.4	20.4	11.8	-0.2	-11.8	-20.4	-23.4
τ_b	0.579	0.613	0.753	0.690	0.568	0.552	0.506	0.560	0.575	0.632	0.596	0.548
τ_d	1.644	1.601	1.423	1.542	1.813	1.870	2.022	1.845	1.790	1.628	1.655	1.723

Lat: 22.63N Long: 120.28E Time Zone: GMT+8

4. Grid Generation and Analysis

Automatic mesh generation (grid generation) has become an essential tool for the finite element or finite volume analyses of practical engineering problems [Lee et al., 2010]. This research takes advantage of automatic grid generation for analyzing and visualizing the thermal distribution of the building envelope in detail. The system generates numerous grids according to the building envelope in a 3D model for representing and analyzing the heat gains. The grid size is defined by the user according to the level of precision they need. The processes of grid generation are shown in Figure 3. Firstly, the user needs to specify the building envelope of the 3D model whose surface is heated by solar radiation directly. At this step, a facet of the 3D model which the user wants to analyze can be extracted. The user then defines numbers of U-points and V-points for determining the grid size which will decide the precision of analysis. The U-direction is the direction in which the data points that defined each row were entered; the V-direction is the direction in which the columns were defined. Next, the system will generate grids according to the user's settings. Finally, the system will calculate the solar radiation for each grid by the above-mentioned numerical model. In the numerical model, the slope of each facet will affect the calculation of solar radiation because different slope will mean different levels of reception of sunshine, such as 0° for the floor, 45° for the roof and 90° for a wall, as shown in Figure 4. The calculated results (shown in Table 2) show that different slopes are differently affected by the sun. The system will then apply color schema to visualize the result of differential solar radiation received. Following this, we can easily determine how solar radiation influences the thermal distribution of building envelope.



Step 1: Specify building envelope

Step 2: Define U-points and V-points

Step 3: Generate grids

Fig. 3: The processes for grid generation

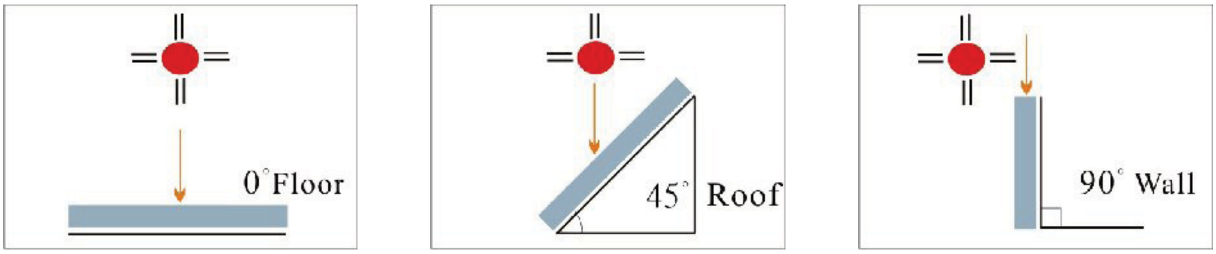


Fig. 4: The interactions between solar radiation and slope on the building envelope

Table 2: Parameters for different slopes of building envelope in Kaohsiung city

Slope	$E_{t,b}$ (w/m²)	$E_{t,d}$ (w/m²)	$E_{t,r}$ (w/m²)	E_t (w/m²)
0°	798.395	227.395	0	1025.790
45°	575.623	250.863	28.510	854.996
90°	15.534	97.755	97.339	210.628

5. Numerical Simulation for Envelope Thermal Distribution Analysis

5.1. System Framework

The visual thermal distribution simulation system is developed based on the Building Information Model which includes a 3D model, climate parameters, time, and area data. The implementation of the system was carried out in the MicroStation Visual Basic for Applications (MVBA) environment. The Bentley MicroStation supports visualization of the 3D building model and provides some capabilities for 3D object manipulation and information query. Application Programming Interfaces (APIs) are also provided for functionality extensions. The system has four main modules, which are described as follows: (1) Parameter Configuration: this module provides functions to assist the user with configuring the relevant parameters; (2) Grid Generation Module: the user can specify the building's envelope and grid size for grid generation; (3) Calculation Module: this module calculates the required value for solar radiation according to input data; (4) Analysis for Solar Radiation: this module is responsible for analyzing the result of the solar radiation calculation. Finally, the system will apply the specific color schema to visualize the result of solar radiation analysis for the user to easily understand the thermal distribution of building's envelope.

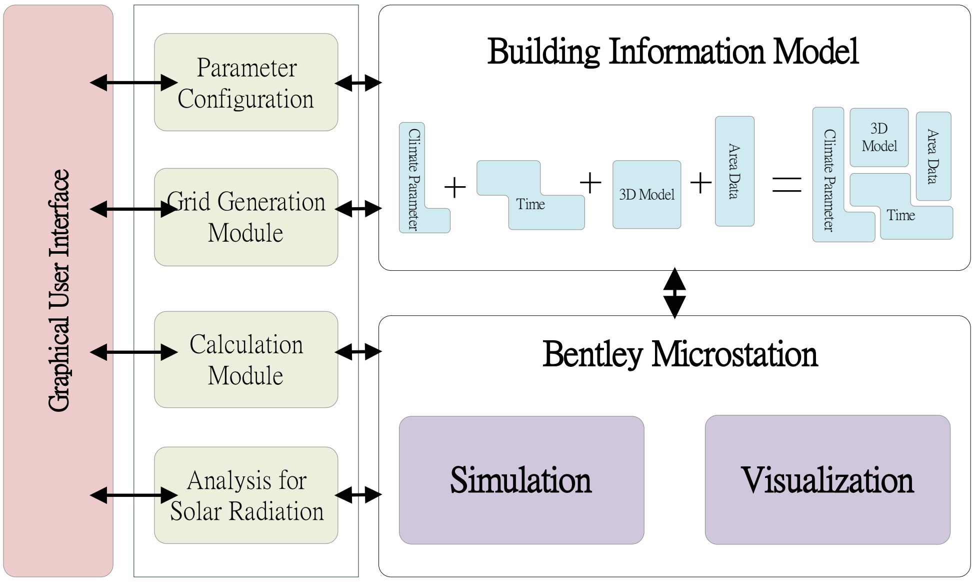


Fig. 5: System framework for visual thermal distribution simulation system

5.2 Example

Figure 6 illustrates the main graphical user interface (GUI) of the visual thermal distribution simulation system. Five functionalities are provided to the user: (1) Project, (2) Setting, (3) Grid Generation, (4) Calculation, and (5) Analysis. In this section, we demonstrate the system using a simple model for testing. Firstly, planner creates a new project and configures the related information, such as project name, location, time zone and building data; the system will retrieve the required data from the database for calculation and analysis (see Figure 7(a)). Secondly, the planner will specify the surface of the building envelope and define numbers of U-point and V-point for grid generation (as shown in Figure 7(b)). Grids size will affect the precision of solar radiation calculation. Next, the system will calculate the beam (Et,b), diffuse (Et,d) and ground-reflected (Et,r) solar radiation components for each surface of grid using the calculation module. The system will then analyze the total solar radiation for each building envelope and display the results using a tree view, as shown in Figure 7(c). The planner can then click the tree-node of the particular building envelope to view the related information. Finally, the system will apply color schema to visualize the result of solar radiation, as shown in Figure 7(d). The 3D objects in the building model are highlighted in different colors depending on their thermal distribution statuses. Table 3 shows the color scheme implemented in this work.

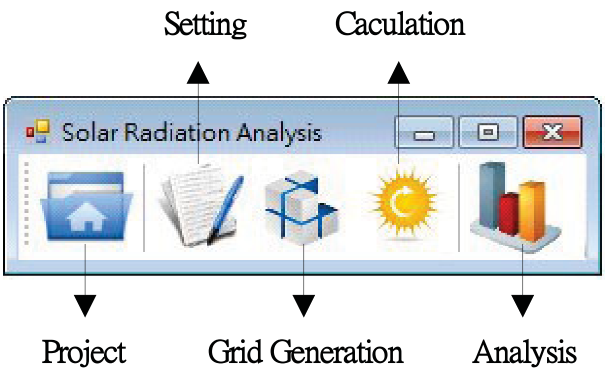
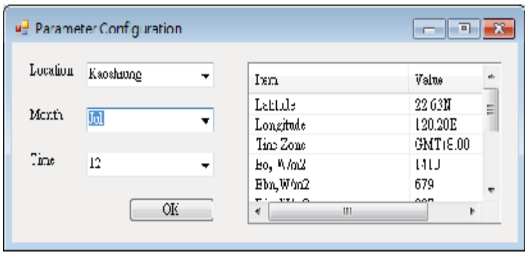


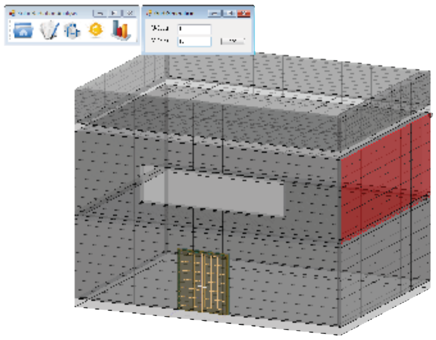
Fig. 6: Graphical User Interface

Color		Solar Radiation
	Blue	200 ~ 400 (W/m²)
	Green	400 ~ 600 (W/m²)
	Yellow	600 ~ 800 (W/m²)
	Orange	800 ~ 1000 (W/m²)
	Red	>1000 (W/m²)

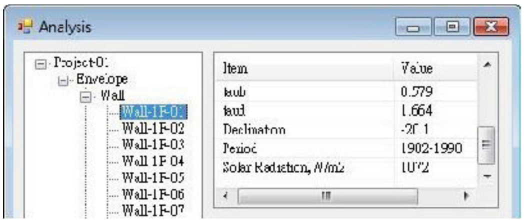
Table 3: Color schema for solar radiation analysis



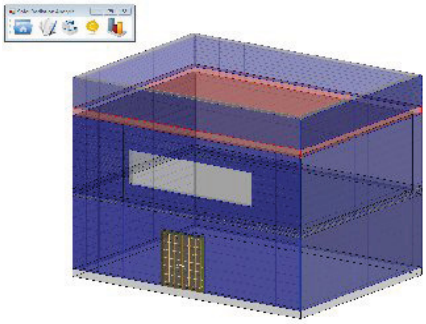
(a) Configure the building parameters



(b) Generate grids



(c) Calculate solar radiation



(d) Visualize the value of solar radiation on surface

Fig. 7: Example of visualization of solar radiation of a building

6. Conclusions and Suggestions

The thermal distribution of a building's envelope is a key factor in building design, affecting the use of energy for air-conditioning. Due to the long-term outdoor exposure of a building to solar radiation, its indoor temperature can be significantly affected. If a planner can understand the building's thermal distribution at early stage of design, aspects such as ventilation design can be improved to reduce heat gain of a building's envelope and ultimately reduce usage of air-conditioning. A visual thermal distribution simulation system was developed in this research to facilitate planners' understanding of buildings' thermal distribution at the early stages of development. This enables planners to detect thermal issues early, provide feedback and make adjustments in order to achieve a green, energy-saving building. A simple model was used as an example to demonstrate the workings of the system. In future work, synthetic considerations will be made of the three heat transfer modes: (i) air convection, (ii) radiation through windows and doors, and (iii) heat conduction between the building materials, to calculate the thermal distribution more accurately.

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APPLYING 4D SIMULATION IN DISASTER EVACUATION ROUTE PLANNING

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ABSTRACT: *The streets of Taiwan are complex and crowded. These road systems, normally utilized for carrying heavy traffic flow, at regular hours, shift to the end of refuge spaces and rescue pathways in post-disaster situations. Presently, these road systems are not used effectively and efficiently in post-disaster situations because of the lack of good disaster evacuation route plans. A great deal of effort has been invested in planning disaster evacuation routes. Therefore, this paper proposes a 4D simulation system to assist planners in planning disaster evacuation routes effectively and to visualize the plans over time. This research considered the various factors impacting upon the planning of an evacuation route, including road width, number of lanes, topology, traffic flows and number of victims, to propose a numerical model for analyzing evacuation routes. Human behavior is another key consideration when planning disaster evacuation routes. For this reason, modeling of psychological variables to enhance prediction accuracy of human behavior during evacuations has been conducted in this research. The implementation of the 4D simulation system was carried out in the MicroStation Visual Basic for Applications (MVBA) environment. In addition, a simple man-made disaster is used as an example to demonstrate the applicability and feasibility of the 4D simulation system. In this system, the 3D objects in the urban model are highlighted in different colors, depending on their statuses of evacuation during simulation. In this way, a planner can find and utilize relevant and necessary data for planning evacuation routes in a more direct and efficient manner to mitigate the effects of the disaster.*

KEYWORDS: *4D, Visual Simulation, Evacuation Route Plan, Man-Made Disasters, Human Behavior*

1. Introduction

Efficient evacuation route planning is currently an issue of major importance due to increasing risks from both man-made accidents and natural disasters. As any disaster occurs, it is important to move people to refuges quickly to keep them safe. In Taiwan, avenues and streets are complex and crowded due to space limitations and the high population density. Having effective evacuation route plans can reduce risks both to lives and to property. Especially in urban disasters, effective evacuation routes are essential to mitigating the effects of the disaster by enabling victims to escape from the disaster zone and reach refuges quickly and safely [Chang, 2007]. Both natural and man-made disasters require that emergency personnel be able to move affected populations to safety in as short a time as possible [Zhou, 2010]. Many evacuation models have been proposed in the literature [Pidda et al., 1996; Park et al., 2004; Pelechano et al., 2008; Zheng et al., 2010; Pel et al., 2010; Duanmu et al., 2010]. The general principle from these various models is that factorial design of evacuation routes influences the efficiency of the evacuation route plan. In this research, the main emphasis is on man-made disaster situations, and the main factors affecting evacuation route efficiency will be considered, including road width, number of lanes, topology, traffic flow, number of victims and importantly, human behavior. The use of specific human characteristics in evacuation models is aimed at enabling realistic predictions and realistic problem-solving. A numerical model for analyzing evacuation routes is proposed based on the above-mentioned impact factors. Having developed the evacuation model, the evacuation process is simulated. Many researchers currently utilize simulation systems to find optimal evacuation routes. Thompson and Marchant proposed and conducted fluid modeling and computer modeling to simulate extensive throngs during evacuation in the Simulex [Thompson et al., 1995]. While a great deal of effort has been put towards planning disaster evacuation routes, there has been a lack of dynamic simulation in 3D environments. In the past decade, 4D technology, which binds 3D models with their corresponding time dimension, has emerged and developed rapidly. This is mainly due to the increasing recognition from the construction industry on the benefits of using 4D technology for increased productivity, improved project coordination, and optimization of on-site resources [Hsieh et al., 2006]. Therefore, this paper proposes a 4D simulation system to overcome the shortcomings of previous research, helping planners to plan disaster evacuation routes effectively, and to visualize the plans over time. The implementation of the 4D simulation system was carried out in the MicroStation Visual Basic for Applications (MVBA) environment. A simple man-made disaster is also used as an example to demonstrate the applicability and feasibility of the 4D simulation system developed in this research. For effective visualization, this research also defines the specified color schemes for illustrating different statuses of evacuation. In this way, planners can find and utilize relevant and necessary data for planning evacuation routes in a more direct and efficient manner for mitigating the effects of the disaster during simulation.

2. Human Behaviour Analysis For Disaster Evacuation

Generally, disasters occur suddenly and unexpectedly. People usually do not have enough time to rationally think of the appropriate courses of action to take, and thus almost always follow their instincts to run away from danger when a disaster strikes. In evacuation model analysis, the changeable nature of human behavior is difficult to predict and apply or feed into to any model. John Leach's Dynamic Disaster Model describes three phases and five stages of the occurrence of disasters, comprising a Pre-impact phase (Threat Stage and Warning Stage), an Impact phase, and a Post-impact phase (Recoil Stage, Rescue Stage and Post-traumatic Stage) [Leach, 1994]. In each phase and stage, the particular sets of human behavior will appeared in response to evacuation processes, with significant differences in people's cognitive, emotional states and overt behavior across these phases and stages. During the Impact phase, heavy stress and denial of life-threatening events will hinder effective evacuation [Vorst, 2010]. For evacuation route analysis, we not only need to consider impact factors of the environment; we also need to consider human behavior during the disaster. Some typical human behaviors during disasters have been proposed by various researchers. Murosak generalized expected human behavior during evacuation in general disasters, such as avoidance behavior, phototropism, conformity behavior, straight characteristics, openness characteristics and proximal characteristics [Murosak, 1993]. Chang showed that the actions of people during evacuation have three main characteristic: Left Turn, Shortcut and Homing behavior [Chang, 1995]. Lovas proposed nine human behaviors for evacuation models that included working correctly, always turning left, random choice, following planned paths, directional choice, shortest path, frequently used path, model parameters and choice in groups [Lovas, 1998]. Characteristics of people are divided into basic personal situations, knowledge, experience, conditions, personalities and roles [Proulx, 2001]. Liang showed that people choose different evacuation routes according to their gender, age and health status [Liang, 2010]. Kim commented that it is generally very difficult to understand and quantify human behaviors since the factors involved vary significantly with the types of accident and the environment [Kim, 2004]. However, without taking human behaviors into account, any proposed evacuation route plan can neither be considered efficient nor effective. Therefore, some important variables from disaster psychology have been applied into the evacuation model presented in this paper (see Table 1). Modeling psychological variables will enhance prediction of human behavior during evacuations and enhance the accuracy and usefulness of the evacuation model.

Table 1: Human Behavior for Disaster Evacuation

Human Behavior	Explanation
Homing behavior	When people encounter a disaster, they choose the most familiar paths and locations for escape.
Avoidance behavior	When people encounter a disaster, they move away from a fire or other danger.
Phototropism	When people encounter a disaster, they move towards a bright place because they think that is likely to be a safe place.
Conformity behavior	When people encounter a disaster, they feel nervous and will be impaired in making decisions independently, and so most people would follow the crowd.
Straight characteristic	When people encounter a disaster, they choose the straight route because the complicated route is perceived as more dangerous.
Openness characteristic	When people encounter a disaster, they move towards more spacious places because they believe that being in a more open space would help them avoid any secondary damage.
Proximal characteristic	When people encounter a disaster, they choose the closest route or stairs to evacuate in order to save time.

Lee et al. emphasized walking speed as a very important factor in evacuation analysis for human safety [Lee et al., 2004]. Therefore, this paper also considers the average walking speeds of humans. In our system for evacuation route analysis, the types of average walking speed include, for people in a rush: males between 15–40 years of age, women below 50 years of age, children between 6–10 years of age, elderly persons, and woman with a child under 6 years of age (As shown in Table 2.) The system will randomly apply different average walking speeds for different evacuees for the disaster evacuation route analysis to be more realistic.

Table 2: Average walking speeds of humans

Item	Walking speed (m/sec)	Item	Walking speed (m/sec)
Rush	2.5	6–10 year old children	1.12
15–40 year old men	1.52	Elder	0.92
Under 50 year old women	1.38	Woman with a child under 6 years of age	0.72

3. Disaster Evacuation Route Analysis

The objective of this research is to propose an efficient evacuation route plan to assist emergency personnel to evacuate people during a disaster as quickly and efficiently (travelling the shortest distance) as possible. Figure 1 shows the flow chart of disaster evacuation route analysis. The processes of analysis can be divided into four steps:

- Integration

In this research, the system is built based on a 4D model which includes a 3D model and time. The city models, building models and transportation models are imported into the system via the integration module for system analysis and simulation.

- Disaster Definition:

The status of disaster will affect the analysis of the evacuation route plan. Therefore, an advanced definition for disaster type, disaster location and disaster status is required. In this research, a man-made accident will be used an example to demonstrate the system.

- Evacuation Route Analysis

There are two main impact factors of disaster evacuation routes: (1) Human behavior: Users can configure human behaviors into the system for analysis, such as homing behavior, avoidance behavior, phototropism, conformity behavior, straight characteristic, openness characteristic and proximal characteristic. (2) Environmental impact factors: In this paper we consider impact factors such as width of evacuation route, the main routes of traffic flow, number of lanes, topology and number of victims for route and plan evaluation. Users can input the value of each impact factor into the system. The system will then analyze the disaster evacuation route according to these impact factors, and calculate the required evacuation time and distance.

In this research, we define an equation for calculating the degree of congestion. This will form the basis of determining the color code of evacuation routes for effective visualization. This system defines the safety space of humans based on the space requirements of each human for evacuation. The system will then divide the route into several zones to analyze the degree of congestion. As shown in Equation (1), the safety space of each human is multiplied by the number of victims and then divided by the area of the zone. Finally, the result is converted to percentages to represent the degree of congestion.

The degree of Congestion = [(safety space of human * number of victims)/ area of zone]*100%…… (1)

If the degree of congestion is more than 80%, the space would be too crowded, and is represented in red. Between 70% and 80%, the zone is presented in yellow to warn of an impending hazardous space. Congestion of less than 70% will mean that it is not too crowded and will be displayed in green.

- Simulation

The distinguishing characteristic of this system is the ability to visualize the movement of each evacuee in the plan as an animation. Planners can thus easily find and understand the problems encountered during simulation. In this paper, we defined three colors to visualize and differentiate the status of the evacuation routes during the simulation in a 3D environment. Table 3 shows the color scheme implemented in this system. For each impact factor configuration, the time and distance analysis was performed, with each run resulting in a different situation. According to statistical analysis, the optimal evacuation route plan would then be proposed.

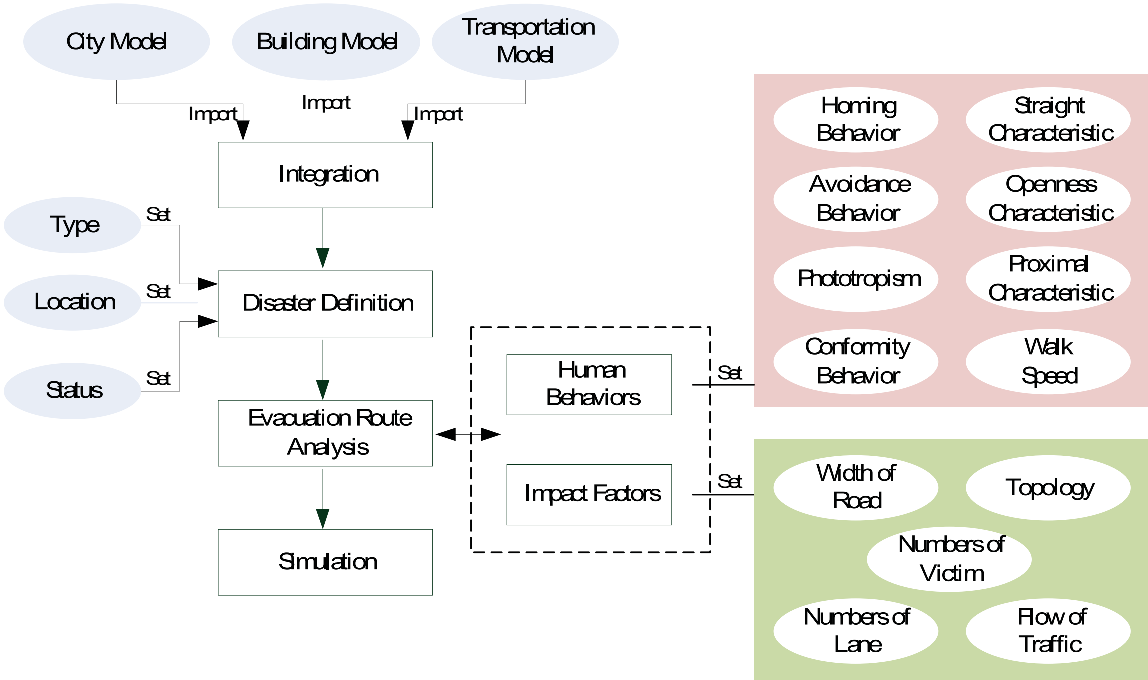


Fig. 1: Flow chart of disaster evacuation route analysis

Table 3: Color Schema for evacuation route simulation

Color		Safety	Efficiency	Congestion
(red)	Red	Dangerous	Inefficient	Too crowded
(yellow)	Yellow	Warning	Moderate	Warning
(green)	Green	Safe	Efficient	Not crowded

4. Demonstration

4.1 System Framework

The system framework of the 4D Disaster Evacuation Route Analysis System is shown in Figure 2. All of the application functions implemented by this system are based on the Bentley MicroStation, which supports visualization of the 3D model with some capabilities for 3D object manipulation and information query. The 4D Disaster Evacuation Route Analysis System can be divided into six main modules: (1) Integration: related 3D model and data can be imported into the building information model; (2) Time Analysis: for calculating the evacuation time; (3) Distance Analysis: for calculating the evacuation distance; (4) Crowd Analysis: for analyzing conflict and the degree of congestion; (5) Visualization: to provide different visualization styles to assist the user in efficiently acquiring relevant information; (6) Simulation: for simulation of different evacuation routes and selection of the optimal evacuation route after several simulation runs.

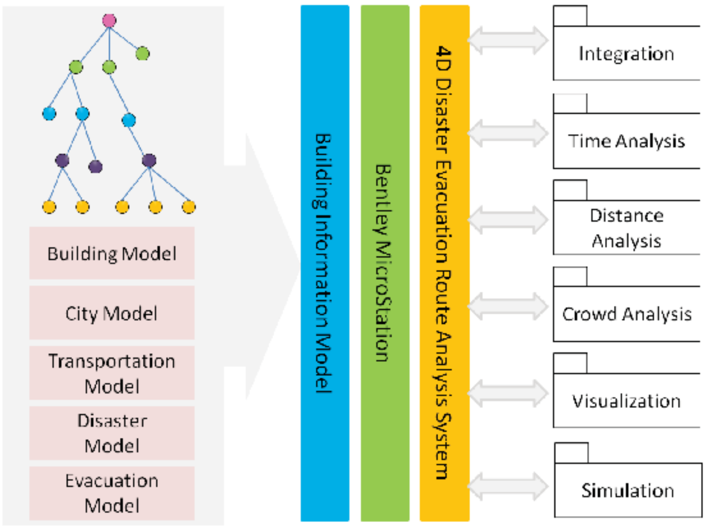
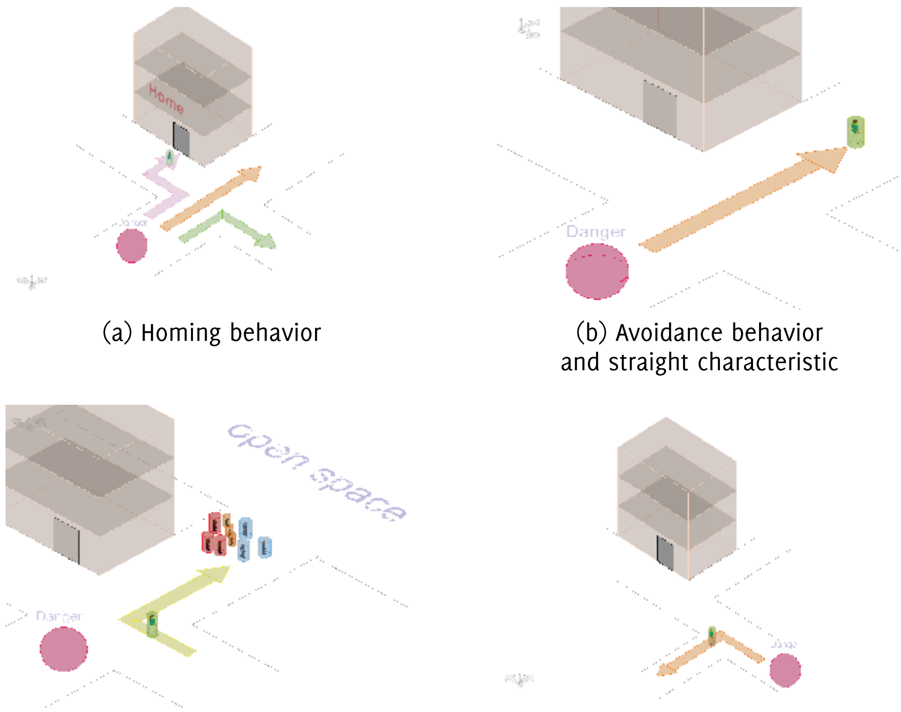


Fig. 2: System framework for 4D Disaster Evacuation Route Analysis System

4.2 System Characteristics

As part of the process of developing and proposing an efficient evacuation route plan, this system also takes human behavior into account. As Figure 3(a) and (b) indicate, humans would select the more familiar paths to evade hazards when they encounter disasters. Most people would also follow a crowd and run toward open areas during evacuation, as shown in Figure 3(c). Figure 3(d) illustrates how humans would attempt to escape using the nearest route to evacuate the disaster.



(a) Homing behavior

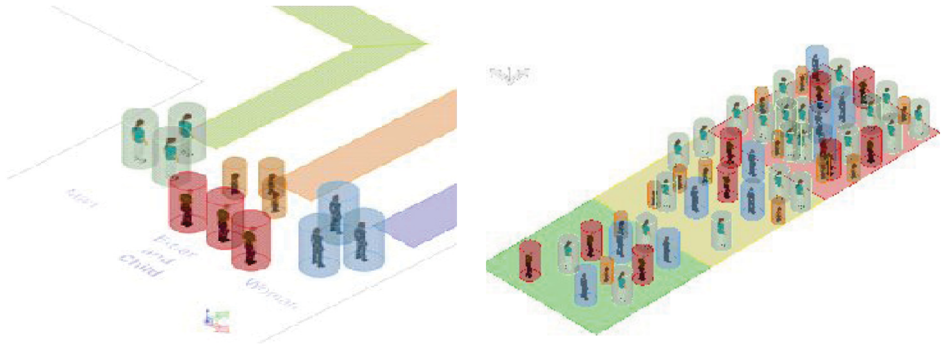
(b) Avoidance behavior and straight characteristic

(c) Phototropism, conformity behavior and openness characteristic

(d) Proximal characteristic

Fig. 3: Applying human behaviors into 4D Disaster Evacuation Route Analysis System

There are three main characteristics in this system. The first is that different kinds of people would form different groups. The system will apply different parameters for different groups for more realistic simulations as shown in Figure 4(a). The second characteristic is visual representation of the status of routes according to the degree of congestion, as shown in Figure 4(b). The third characteristic is 4D simulation of evacuation through time, and this will be shown in the next section.



(a) Different kinds of people forms different groups

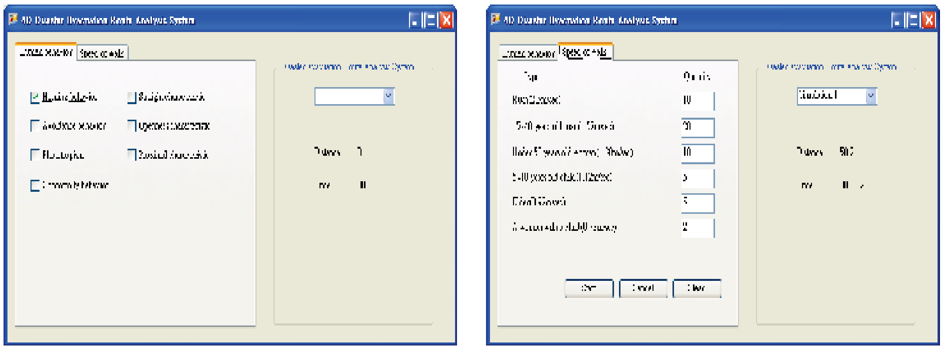
(b) Representing the status of routes visually

Fig. 4: The Characteristics of the 4D Disaster Evacuation Route Analysis System

4.3 Example

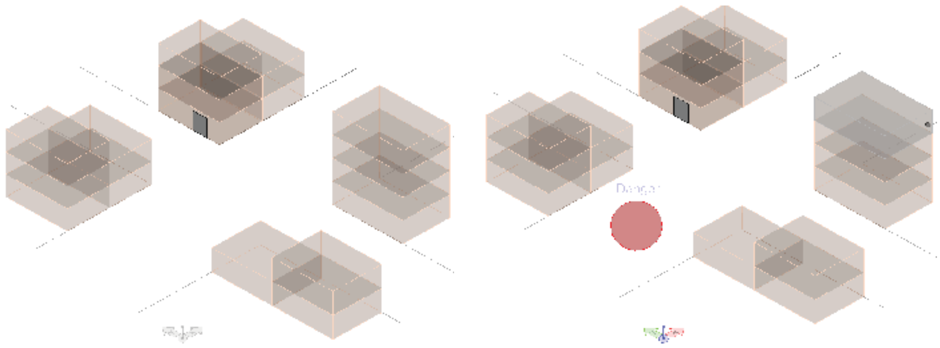
A simple city model was used as an example to test and demonstrate the functionality of our 4D disaster evacuation route analysis system, as shown in Figure 5 and Figure 6. Figure 5 illustrates the main GUI of the 4D disaster evacuation analysis simulation system. Before system analysis and simulation, the planner needs to configure the types of human behavior to be simulated (as indicated by Figure 5(a)). The planner would then set the numbers and kinds of humans involved (as indicated by Figure 5(b)). Different kinds of human have different walking speeds, and these settings would make evacuation route simulations more realistic. When the planner clicks the “Start” button, the system will start to simulate according to the user’s settings, and then calculate the distance and time of evacuation for simulation. This system generates a multitude of efficient evacuation routes that can be analyzed and visualized for manual identification of good solutions. Planners can then select the best solution according to their particular objectives.

Figure 6 shows the processes of the 4D simulation. First of all, users can create 3D models of building objects within the system. The disaster status and location will also be defined for analysis. Next, the system will randomize the numbers and kinds of humans according to user’s setting. Finally, the system will run the simulation and automatically calculate and analyze evacuation distance and time for reference.

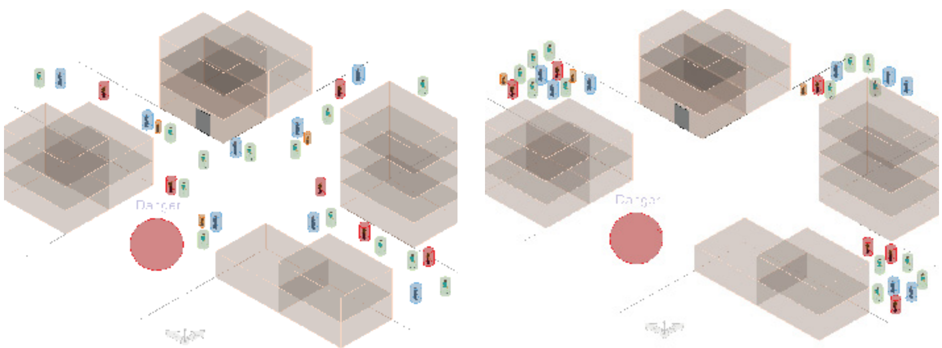


(a). Configure the human behavior (b). Calculate distance and time

Fig. 5: The setting GUI of 4D Disaster Evacuation Route Analysis System



(a) Import the 3D model into system (b) Define the status and location of disaster



(c) Randomize human models (d) Simulation results

Fig. 6: The processes of 4D simulation

5. Conclusion

An efficient evacuation route plan can decrease the impact of the disaster in terms of injuries and loss of lives. At present, most disaster evacuation research has focused on the effects of disasters with regards to environmental impact factors. However, human responses also play an important role during actual disaster evacuation. This research demonstrates human-oriented modeling and simulation. In this research, we attempted to integrate the environmental impact factors and human behavior analyzed in the literature into a single evacuation model. This research also applies 4D simulation which visualizes 3D models through time so as to dynamically simulate the status of evacuation routes. The implementation of 4D Disaster Evacuation Route Analysis System is based on the Bentley MicroStation which is also responsible for the demonstrated visualization capabilities. In this system, planners can set up the disaster status and impact factors, and then run the system to simulate analyze evacuation routes according to various possible user configurations and surrounding environments. The system also analyzes evacuation time and distance for each simulation, and proposes the shortest time or distance of evacuation route after several simulations have been run. There are three major characteristics of 4D Disaster Evacuation Route Analysis System: (1) visual representation of route status using different colors such as red for dangerous, overcrowded situations. (2) 4D simulation which enables the planner to quickly grasp the situation at different stages of the disaster. (3) representation of different kinds of people and categorizing them into different groups, for example, modeling different walking speeds of women and men of different ages, the elderly and children. Through the presented test scenario, this system demonstrates its ability to provide a more efficient evacuation route, and also presents the planner with a full view of statuses during disaster evacuation through 4D simulation.

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PROJECT SPECIFIC BUILDING INFORMATION MODELLING (BIM) PLANS AS A VEHICLE FOR KNOWLEDGE TRANSFER

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KEYWORDS: *organisational learning, knowledge management, knowledge transfer*

1. Introduction

This paper investigates the problem of how an organisation can learn when it is individuals that learn and have knowledge (Argote & Ingram 2000). The research has been undertaken in the area of Knowledge Management, Transfer and Organisational Learning theories and the problems associated with them (Senge 1992, Szulanski 2003). The contribution to these theories is that a potentially consistent and practical way of transferring knowledge from individuals that have it, to those that need it, at the right time, within an organisation has been identified.

To deliver a construction project, people are brought together, often for the first time, to achieve a common goal. The project is a temporary framework for learning and when the project is completed the people disperse. What was known and learned, often with great difficulty, during that project is then 'forgotten' by the organisation, if not the individuals. On future projects new teams are created and much of the same 'lost' knowledge then has to be re-acquired (Argyris and Schon 1996)

This paper proposes that the use of project specific Building Information Modelling (BIM) plans in a structured and disciplined way across the organisation allows the organisation to learn, retain, retrieve and pass on knowledge to future projects. The research has identified that where a BIM plan was used on a Case Study project people were obliged to implement standards and protocols that led them automatically to follow the right course of action. The standards and protocols within the BIM plan articulate the requirements of other team members and how they are to be delivered.

Using Action Research on the case Study it is possible to demonstrate that the codification of the standards and protocols within the project specific BIM plan 'embodied' the knowledge required to understand and provide the disparate groups within the project with the information they need at the right time. The robustness of the process (Kagliouglou, Cooper, Aouad 1998, Haigh and Sarshar 2000) and the discipline of the application are more influential than the information in the databases which support BIM in achieving success.

2. Problem Identification

Much has been written relatively recently about Building Information Modelling and its potential for improving efficiency within the construction industry. In October 2008, a decision was made by the CEO of Skanska Johan Karlstrom, to adopt BIM across the organisation. On all new Design and Build projects going forward from January 2009 where the design had not yet started.

The broad concept of BIM was described and also the areas where the application of BIM might be beneficial. The detail of what, how, when, why and by whom was not explained. Each Business Unit across Skanska had to identify a methodology for identifying how best to implement BIM on any given project.

In the UK Skanska had been successful in winning bids for a number of Private Finance Initiative (PFI) hospital projects. In simple terms these projects are part financed, design and constructed and then the facility maintained for a 30 – 35 year concession period by Skanska. Some issues had arisen during the maintenance phase of the hospitals and investigation had identified certain shortcomings in the production and subsequent retrieval of information required by the facilities management. It was proposed that BIM may provide potential solutions to these issues on future projects in terms of structuring the data, its capture and the future retrieval from the applied technologies.

2.1 Information gathering from existing hospitals

As part of the process for finding out how BIM could assist with rectifying the issues that had come to light during the facilities maintenances phase of the projects, several recently completed and operational PFI hospitals were visited. These were hospitals at Walsgrave (Coventry), Derby and Mansfield. On each of those projects it was identified that there were varying formats and quality in the production of the room numbering system, the asset register (which are key components of the asset coding structure) and the operation and maintenance manuals.

This lack of consistent structure and discipline in the structure of the data capture meant that a lot of extra and difficult work was created on each project to try and come up with the required information to manage the facilities during the maintenance phase. There was also no transference between the projects to create consistency within the company even when the issues had been resolved at a local level. This means, for example, that facilities management may eventually know what and how many assets they have on a particular project but the lack of a standard format means there is no easy way of knowing what and how many assets there are across the whole of the estates portfolio. This in turn leads to difficulty in gathering information and gaining an understanding of the overall performance and consistency of any given type of asset. Are they efficient, reliable etc. or in other words are the right products being procured in terms of life-cycle maintenance and replacement criteria, which if not efficient can become very costly over many estates over long concession periods.

2.2 Problems Identified and the consequences

From the Facilities Management (FM) perspective the most significant difficulties were experienced because of the lack of consistency and structure in the following

- **Room numbering protocol**
  The consequential problem associated with the lack of a proper room numbering protocol is that it is difficult to identify geographically where assets to be maintained or repaired are located. The hospitals investigated each had about 7000 rooms over large estates. As can be appreciated much wasted time and effort accrues merely finding out where a particular piece of equipment to be serviced or repaired was located.

- **Asset Register**
  In an incomplete and inconsistently formatted asset register FM had difficulty in knowing exactly what assets and how many there were to be maintained within the hospital estates. Not knowing, for example, how many pumps, what size, type etc. make it impossible to plan maintenance and effect repairs efficiently and cost effectively.

- **Asset coding structure (of which room numbering and register form part)**
  In an incomplete and inconsistent asset coding structure problems arise as identified above because of the difficulty in obtaining exact geographic location and knowing the type and totals of assets on the estate. Also the asset coding structure identifies to what particular type of system the asset belongs. For Example mechanical, electrical and then what sub-system eg power or lighting, water or air handling and this in turn informs how critical the system is (there are financial penalties levied for non provision of service) and which specialists are required to undertake the maintenance or repair.

- **Operation and Maintenance (O&M) manuals**
  The lack of detail and consistency in the structuring of the O & M manuals has also given rise to problems. They should have contained details of what the asset is and its identification code, from whom it was obtained, warranties, installation date, servicing requirements etc. Again if all the required information is not logically recorded and retrievable there is lots of efficiency and wasted effort and time trying to obtain this information long after the asset is installed and after it has started to be problematical.

3. Preventing Future Problems

From the information gathering on the previously named PFI hospital projects another exercise was undertaken at another very recently completed PFI project at Walsall manor hospital. This exercise undertaken jointly with the Skanska Facilities services (SFS) and Skanska Infrastructure Development (SID), the concession holder and Skanska UK Construction (SUK). The purpose of this undertaking was to engage broadly across the company to gain participation, consensus and agreement for the format of some defined and structured protocols for the asset coding structure (which incorporated the room numbering protocol and the asset register) and the O & M manual template.

These documents were prepared and were ready for use on the next PFI hospital project bid which was at Papworth hospital, Cambridge. It had been determined by the edict from the CEO that all design and build projects would implement BIM. In order to achieve that, as the result of a separate work stream, each project would formulate a specific BIM plan. This would be agreed by all the 'principals' on a project, such as the designers, constructors, concession holders and operators, The plan would capture the details of the practical interpretation and how the outputs from the plan would be delivered on the project.

As the Papworth bid was one of the early projects to consider the formulation and implementation of a BIM plan it was considered highly likely that the BIM plan might provide a practical vehicle for transferring the lessons learned as knowledge onto the project. It was decided to test this hypothesis in the form of action research using the Papworth bid as a Case Study and only the shortcomings in the facilities management process were selected to form a practical and manageable scope for study.

The creation of standards and protocols is not peculiar to BIM. The mandatory use of the standards created from feedback as part of an also mandatory process of compiling and subsequent implementation of a project BIM plan is what ensures that the knowledge becomes embodied in the process. In previous projects the knowledge had either nor existed or had been lost to the organisation.

4. Case Stude and Action Research

The proposition that the BIM plan may be a suitable vehicle for knowledge transfer arose from the process of obtaining the feedback from the previous PFI hospital projects See Fig 1.

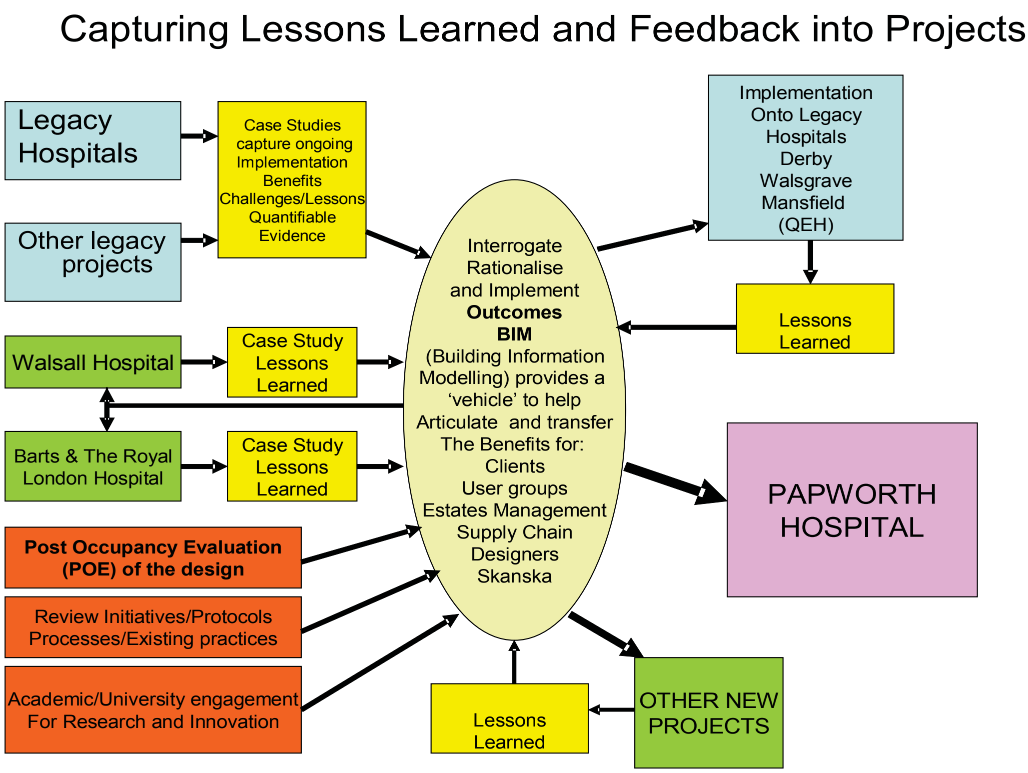

Fig. 1.

It had been apparent that many people involved with these projects had been unaware of the need for structuring the information for future use. Although the structures had been formulated for use on the Papworth bid there still arose the difficulty of making people aware of the existence of the standard formats and then to actually get them to be used.

Structured interviews and then follow up meetings were held with ten senior participants in the design, the management of the design, the construction, facilities management and the concession holder. The process involved an initial meeting to establish the individual's awareness and understanding of the concept of BIM. The establishment of their understanding and appreciation of the fact that standard template formats existed and whom their use would benefit was undertaken at the same meeting.

Only one of the ten participants was aware that the structured format of the data would be of benefit to the facilities managers. One other was aware that the ability to retrieve the recorded information would benefit the concession holder. That meant that eight out of ten had no understanding of the need for nor did they know of the existence of the templates and who their use would benefit. The same eight also had no notion that the project would have to formulate and implement a BIM plan.

A follow up meeting was held at which the templates were shown to the participants together with an explanation as to who would benefit from their use and where the document could be retrieved from for future use. Also at this meeting it was explained that the Papworth project would be implementing a BIM plan and the use of the templates were pre-requisite constituents for the agreement of the plan. Their use during the project will provide the information in the structured format that had proved to be lacking on all the previous PFI hospital projects. A structured guidance procedure for the implementation and contents for project specific BIM plans has been produced and their use is mandatory.

The structures and standards are aligned to the Computer Aided Facilities Management (CAFM) system. This system, linked through the helpdesk, facilitates the discrete and efficient maintenance of the building for the client, occupants and users. The CAFM system also provides automation for the Pre-Planned Maintenance (PPM) as well as statutory and contractual obligations. Implicit in the BIM plan were other elements of feedback beyond the study area of this Case Study The data requirement for the optimum management of the life-cycle fund has also been articulated and can be captured within the Papworth specific BIM plan. The implementation and other agreed requirements for BIM are also captured in the Papworth BIM plan. The use of the standards, protocols, co-operation and collaborative participation in the formulation of the BIM plan is a requirement within the design agreements and sub-contracts.

The 'organisation has learned' from past lessons and Fig 2. shows the Papworth Model which will be implemented on future projects:

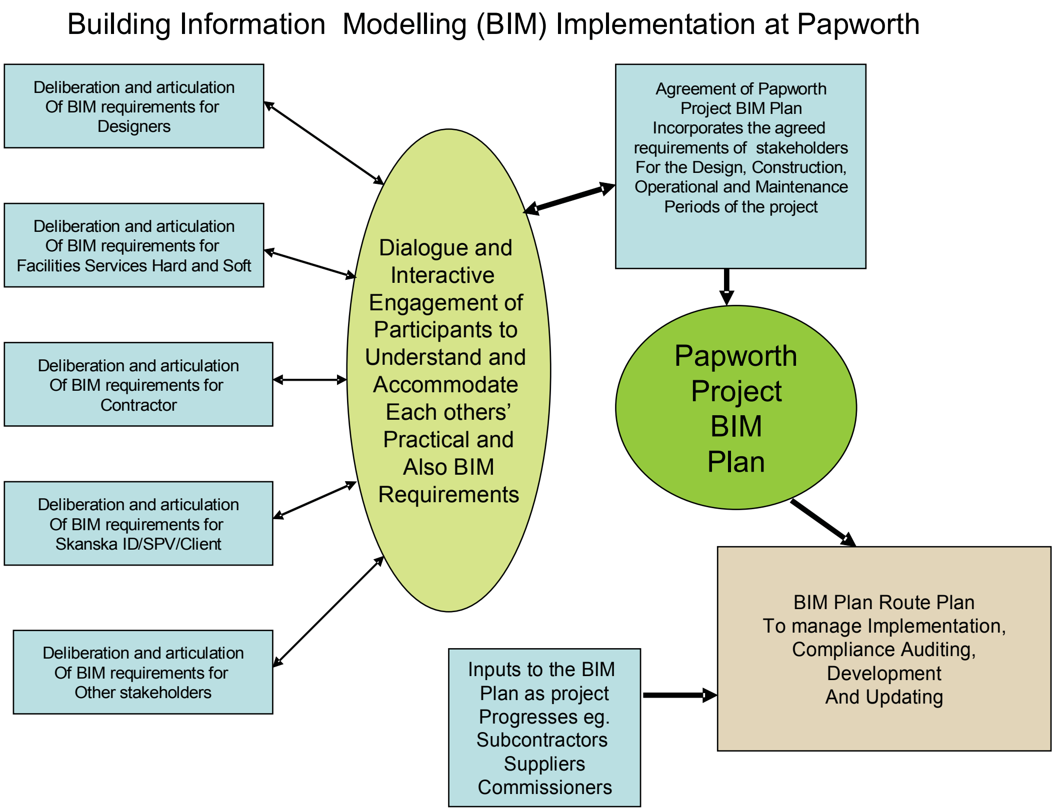

Fig. 2.

5. Conclusion

In the Papworth Case Study some examples of the nature and importance of the codified structures in relation to the efficient implementation of Facilities Management were assessed on several recently completed hospital projects. The levels of understanding of these structures such as room numbering protocol, asset register, asset coding structure, Operation and Maintenance template and how they relate to the Computer Aided Facilities Management (CAFM) system was very low on these projects. This had led to difficulties for the management of the (very large) estates. During the bid process for a similar hospital project the creation of a project specific BIM plan ensured that the required standards providing the right information in the right format would be implemented. Crucially the staff responsible for ensuring these structures would be in place and adhered to early in the design and through construction became aware, where they had not been previously of:

- the existence of standards and protocols
- their importance, why and to whom
- what they were and how they are structured
- where to obtain them
- when to implement them
- what information was required for future use and in what format

This awareness had not previously existed and information had previously been supplied in an ad hoc way that differed from project to project, was incomplete and or even incorrect. This had obviously required much effort later to rectify. This new awareness constitutes new knowledge brought to the individuals on the project because of the BIM plan.

The process involved in creating the BIM plan for the Case Study project involved the active acquisition of feedback (Bordass and Way 2004) from the other projects and it is therefore argued that the knowledge from the previous projects was 'embodied in the BIM plan. The future use of BIM plans and the active and ongoing feedback from other projects means the organisation should retain knowledge that was previously lost.

This creation of standards and protocols is not peculiar to BIM but their mandatory use in an also mandatory process of compiling and subsequent implementation of a project BIM plan is what ensures that the knowledge becomes embodied in the process. In previous projects the knowledge had either nor existed or had been lost to the organisation and so the project specific BIM plan has provided the vehicle for the transfer of knowledge.

The deliberations for BIM also provide an excellent forum for discussing and resolving other issues for which there are rarely structured environments.

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COMPUTER MODELING IN ORGANIZATIONAL AND TECHNOLOGICAL DESIGN

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ABSTRACT: *Construction informatization is a complicated problem which represents the whole complex of issues connected with automation of various construction sub-industries. One of the basic informatization directions is the automation of organizational and technological design (OTD), which means designing the whole process of a future building construction. OTD deals with the issues of time organization of the construction process including logistical support, well-timed delivery of construction material, carcasses and goods to warehouses and construction sites. In practice one can deal with more complicated cases when it is impossible to make the analytic dependence linking system input and output and, therefore, the system analytic model as well. Thus, the classical mathematical approaches become inappropriate for analyzing the situation at the construction site. Simulation modeling approaches are applied in this case. The analytic models neither research the internal structure nor investigate the system behavior. In fact only the connection between input and output is taken into consideration, whereas the system itself remains "a black box". The simulation models are characterized with the absolutely different approach. The system behavior is described in detail in the course of time. The state transition processes are simulated in the way as if they took place in reality. Then the system behavior is observed for the indicated period of time and in accordance with the results one can make a conclusion as to the obtained factors characterizing the output. The main advantage of simulation models is the possibility to modify the settings characterizing the system behavior. One can control time decelerating it in the case of fast processes and accelerating it for modeling the systems with slow mobility. The main direction of modeling OTD problems is the operating time of standardized simulation modules that enables to expand the range of indicated issues. Expanded features of simulation models concerning the obtained results visualization allow to effectively analyze the systems that before have not practically taken into account because of their formalization complexity.*

KEYWORDS: *Computer modeling, simulation modeling, organizational and technological design, construction, CAD, stochastic models, queuing systems, mathematical processes, Markov chains, Chapman-Kolmogorov equations.*

The variety of functions and a wide circle of construction participants predetermine the high intensity of data processes at all the stages of the investment cycle. So the main goal of building complex informatization is the organization, junction and the agreement of these processes, the exception of information duplication, and the support of information consistency.

The construction informatization is a complicated problem which represents the whole complex of issues connected with automation of various construction sub-industries. One of the basic informatization directions is the automation of organizational and technological design.

The rapid complication in the engineering activity during the last decades is characteristic of building systems to the full extent. Alongside with the traditional construction elements (construction and building structures, building machines, work gangs etc.) the building systems started to include the components of modern complicated information economic-organizing and calculating systems (the mechanism of economic management, organization management structures, the automation systems of planning, constructing, managing, etc.).

The constructing process is usually associated with drawing some detail, a junction point, an aggregation, a product. In this sense the construction design is commonly identified with the architectural construction design (a design, a building and a construction function as a detail and a product). There is no discrepancy of principle with the main conceptions of machine-building drawing in this case.

However, the essential unit (as to the content and labour-intensity) of the construction design is the so called organization and technological design (OTD) that is designing the whole process of a future building construction. The organization and technological documents filing has its own peculiarities and significantly differs from the technological design in mechanic or electronic engineering, i.e. in CAD "legislator" branches.

OTD deals with the issues of time organization of the construction process including logistical support, well-timed delivery of construction material, carcasses and goods to warehouses and construction sites. Thus, the modeling of process in OTD includes various problems based on the mathematical processes investigation.

The arrival process of requirements to the construction organization technological system is characterized with

- the number of requirements $n(t)$, arriving at the system per time slot $[0;t)$, where $n(t)$ - is a non-decreasing, non-negaive, integer-valued function;
- the time slot τ between the adjacent requirements, where τ - are the random quantities.

The function $n(t)$ can be set by the joint distribution probability:

$$P_n(t) = P\{n(t_1)=k_1;\ n(t_2)=k_2;\ \ldots\}$$

The probability is set the most simply for the simplest process which simultaneously meets the following requirements:

- stationarity, that is the probability referred to the arrival of the definite number of requirements $P_n(t)$ on the time interval $[0;t)$ depends only on the interval range and does not depend on its location within the time line;
- the absence of aftereffects (prehistory), that is $n(t)$ and $P_n(t)$ do not depend on the events taking place before the time point $t_0=0$;
- ordinariness, it implies a time slot $\Delta t\ (\Delta t \to 0) = dt$, which is characterized with the arrival of the single requirement.

For this process

$$P_1(dt) = \lambda\, dt,$$

is typical, that is the probability of the single requirement arrival is proportional to the time interval and the intensity of the requirements process λ.

The interval length between the adjacent requirements in the simplest process is defined by the exponential distribution law:

$F(\tau) = 1 - e^{-\lambda\tau}$ with the expectation value $M=1/\lambda$ and the dispersion $D=1/\lambda^2$.

The analysis of the process organizational and technological systems in construction proves that most of them come to the queuing systems (QS), that is the systems designated for requirement stream-processing for queuing (fig. 1).

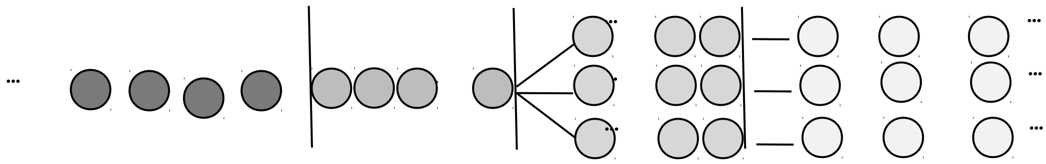

Fig. 1: The QS general structure.

Thus, the solving of the organizational and technological design issues results in pointing out the main QS characteristics:

- input process characterization;
- estimating a queue length and a delay period;
- identifying a number of channels necessary for the effective processing service (identifying the service time);
- output process characterization.

The main factors characterizing the QS are as follows:

- the number of unserved requirements (estimated by the loss probability);
- the number of busy channels (estimated by the probability, that *k* channels are busy while servicing)
- the downtime factor (or the utilization factor) of the QS (estimated as a part of used channels in general).

In the practice of the organization technological design one can deal with the following kinds of the QS:

1. On the pattern of the requirements arrival:
    a. deterministic (occur within the narrow range of issues, when the input process is simplified to the regular one, with the permanent time intervals between the requirements; in practice it means the case of the stable financing, regular material delivery according to the schedule, etc.).
    b. stochastic (occur practically in all cases, when the random perturbation actions of different origin are taken into account).
2. According to the time of the requirements in the queue length:
    a. with unlimited time (they occur while reviewing the building structures, products and materials with lengthy service life deliveries, while reviewing financial processes and designing the support manning of the construction technology, etc.).

b. with limited time (they occur while reviewing the deliveries of the construction materials with the limited service life: concrete, solutions etc.).
c. with the refusal (they occur while reviewing the deliveries of the building structures, products and materials necessary for storing if there are some limitations on storage spaces, etc.).

3. According to the order of the requirements service:

    a. in turn - FIFO - first input, first output (they occur while designing traffic processes while “from the wheels” assembling, while reviewing the issues on organizing the construction equipment repair and considering different requests, etc.).
    b. in the order of the LIFO arrival - last input, first output (they occur while considering the process of the construction material expenditure, the expenditure of products and lengthy storage warehouse materials, first of all, the bulked ones, in some problems concerning traffic processes simulation, etc.).
    c. with priority (they occur while considering scheduling problems that refer to an object erection, the construction equipment repair, consideration of different requests, etc.).
    d. at random (they occur while considering the expenditure of stackable building structures, products and materials, the analysis of financial processes, etc.).

4. According to the composition of the service channels:

    a. single-channel (they occur while considering limited throughput capacity system when traffic streams, repair and service systems are simulated, etc.).
    b. multichannel (they occur while considering the systems with extended throughput capacity, while modeling the schedule of construction object erection at numerous divisions with parallel execution phases, etc.).

5. According to the number of the service steps:

    a. single-phase (they occur while modeling the installment of construction structures, the organization of traffic processes, equipment procurements, etc.).
    b. multiphase (they occur while modeling the work of complex construction brigades, in some systems of construction equipment repair organization, etc., when the output process of service for one phase is the input process for the following phase).

6. According to the pattern of the channel occupancy:

    a. in the order of the channel release (they occur while modeling the work of complex construction brigades, specialists on repair and service, while analyzing the work of construction machines and mechanisms).
    b. with the strict order of associativity of the channel and the requirement (they occur while modeling the work of the specialized construction brigades, specialists on repair and service, while analyzing the work of specialized construction equipment).

7. According to the limitation of the requirements arrival:

    a. open-loop - with the unlimited process of requirements (they occur while modeling procurement systems, traffic processes, while considering requests, etc.).
    b. close-loop – with the limited process of requirements (they occur while modeling systems of the user service, as a rule, connected with the repair of limited base of machines and equipment when after service the requirement reenters the input of the same QS).

The functioning of the simplest QSs (single-channel, open-loop, with unlimited expectation and the simplest requirements processes) is formalized in the most common way. The conduct of such a system can be represented as the process of state transitions: X_o - the system includes no requirements, X_1 - the system includes a *1* requirement, ..., X_n - the system includes *n* requirements. In this case the QS work is illustrated with a state graph (fig. 2).

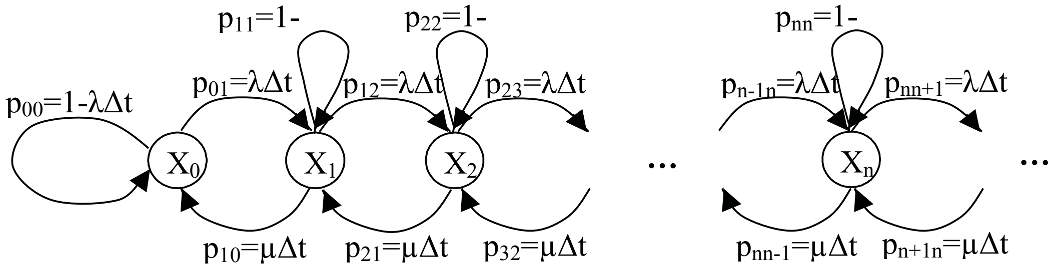

Fig. 2: The state graph of the simplest QS functioning.

The probability of the arrival (service) of the next requirement (the probability of the transition in the next or the previous state *X*) for the period of time Δt for the stationary process is proportional to the time and the process intensity (λ - for input and μ - for output). If the processes, acting in the QS, are ordinariness, that is for the period of time Δt exactly one requirement enters or it is serviced, skipping through the adjacent state is impossible. The probability to keep the same state can be defined on the assumption of the probability of the divisible group of the disjoint events: the integrated probability for all the arcs proceeding from the event, must be equal to *1*.

$$\Pi_1(\Delta t) = \left\| \begin{matrix} 1-\lambda\Delta t & \lambda\Delta t & 0 & 0 & \ldots & 0 & 0 & 0 \\ \mu\Delta t & 1-(\lambda+\mu)\Delta t & \lambda\Delta t & 0 & \ldots & 0 & 0 & 0 \\ 0 & \mu\Delta t & 1-(\lambda+\mu)\Delta t & \lambda\Delta t & \ldots & 0 & 0 & 0 \\ \ldots & & & & & & & \\ 0 & 0 & 0 & 0 & \ldots & 0 & \mu\Delta t & 1-(\lambda+\mu)\Delta t \end{matrix} \right\|$$

For the QS satisfying the limitations of Markov chains (the process probabilistic characteristics in the future depend only on the current state and do not depend on the pre-history) Markov theorem can be applied:

$P_n = P_o \cdot \Pi_1^n$, where

$P_o = \{p_o(t_o), p_1(t_o), \ldots, p_k(t_o)\}$ - the row vector of containment probabilities in the condition $X_o, X_1, \ldots, X_k$ (in the system *o, 1, ..., k* requirements) in the initial point of time;

$P_n = \{p_o(t_n), p_1(t_n), \ldots, p_k(t_n)\}$ - row vector of the containment probability being in the condition $X_o, X_1, \ldots, X_k$ through *n* system functioning steps.

The row elements form the divisible group of disjoint events and the total probability on all the vector elements equals to *1*.

$$\sum_{i=1}^{k} p_i(t) = 1.$$

In fact Markov`s theorem shows that with a sufficiently large *n* the system tends to the limiting state, which is described by the vector P_n.

To describe the transition in the modeling one can apply Chapman- Kolmogorov differential equation:

$$\begin{cases} p_0^{'}(t) = \lambda p_0(t) - \mu p_1(t) \\ p_1^{'}(t) = \lambda p_0(t) - (\lambda + \mu) p_1(t) + \mu p_2(t) \\ \ldots \\ p_k^{'}(t) = \lambda p_{k-1}(t) - (\lambda + \mu) p_k(t) + \mu p_{k+1}(t) \end{cases}$$

For the stationary process the derivatives equal to *0*: $(p_i^{'}(t) = 0)$ and the system degenerates into the algebraic equations solved as Cauchy problem.

However the given above review of the QS being considered in the organization technological design in construction shows that in practice one can deal with more complicated cases. Today the process of designing and building (structure) erection in construction is much less formalized that the process of creating a circuit board, an electronic circuit and a machine building detail. It is determined by the following reasons:

- the organizational technological design in construction is not only the process of drawing some product, even complicated enough, it is the design of the most complex man-machine system i.e. the future environment designated for realization of architects` and designers` ideas;
- the construction of any buildings, structures, complexes implies a connection with the territory which determine the concrete construction conditions (climatic, nature conservation, economic, transportation, social, etc.);
- every construction site differs in a composition, the type and the designation of the objects under construction, the structure and the technological level of construction organizations, the base of building industries, builders` community and many others. That is why there are objective complications in projects typification and unification which hampers the CAD adoption immensely;
- while making some product and an aggregate for a single period of time in machine building a limited number of specialists, instruments, machine tool stations etc. “cooperate” with the product (directly participate in the process of its creation). At the same time due to the complicity, the extent and the big size of the “product” under construction (that of buildings and structures) the whole builders communities, a great quantity of machines, mechanisms and transportation vehicles can take part in the erection process simultaneously;
- if the assemblage (building and assembly jobs) is taken into consideration, the quantity of utilities, their size, problems with warehousing, keeping, the agreement in their delivery, etc. become important construction issues that should be solved within the organizational and technological design stage;
- the future “product” size, stationarity and immobility predetermine mobility of production means and producers themselves and therefore it requires accounting not only temporal, material but also the dimensional aspect as well (one should define not only the issues of when and which material resources will be essential but also the way they will interact at the construction site or in space). If the first issue (scheduling problem) was paid much attention while applying machine-computing technique, the second issue (the automation of spatial organization in construction) is not investigated to the full extent;
- in construction (even more than in other spheres) the aesthetics and design requirements being primarily important and practically cannot be formalized.

Thus, one can often deal with the situation when the analytical dependence linking the system input and the system output, and therefore, the system analytical model cannot be created. Accordingly the classical mathematical methods are inappropriate to analyze the situation at the construction site. Simulation modeling approaches are applied in this case.

The analytic models neither research the internal structure nor investigate the system behavior. In fact only the connection between input and output is taken into consideration, whereas the system itself remains "a black box". The simulation models are characterized with the absolutely different approach. The system behavior is described in detail in the course of time. The state transition processes are simulated in the way as if they took place in reality. Then the system behavior is observed for the indicated time period and in accordance with the results one can make a conclusion as to the obtained factors characterizing the output.

The simulation models applied in organizational and technological design have the following peculiarities:

- the models always depend on time;
- the results are always identified with the random character of investigated processes.

It is important to take into account that every particular model realization must be regarded only as the random sample element. The conclusions of model-based object are made as a result of the trial set statistical manipulation.

The main advantage of simulation models is the possibility to modify the settings characterizing the system behavior. One can control time decelerating it in the case of fast processes and accelerating it for modeling the systems with slow mobility.

Depending on the initial data on the object under investigation one can apply two methods of simulation modeling:

- the method Δt;
- the singular conditions method.

The method Δt implies step-by-step modeling of the system state transition within the equal time intervals Δt. It is evident that the higher the modeling accuracy, the less is the time step under consideration. However if Δt decreases, the quantity of interactions increases and the labour intensity of realization of model raises.

Within the framework of the singular conditions method not the state transition, but the length of the state stay is modeled. The labour intensity of the method is much lower, but its realization requires availability of the raw data that characterize not the probability of the state transition, like in the method ➋*t*, but the lead time in the system.

The obvious challenge for the simulation model realization is the collecting of valid statistical data in order to get stochastic characteristics describing the investigated object. However the organizational and technological design can solve the similar problem, which makes it possible to significantly expand the range of the current tasks.

The detailed analysis and simulation of the processes inside the system imply its detailed decomposition into subsystems, elements and interrelations with designing particular models for each fragment. This work aimed at turning the general model construction into the integration of type blocks, each of them presents the simulation of the standard stochastic process with controlled features (expectation value, dispersion and some others).

The applied software for the practical model realization plays an important role in providing the efficiency in simulation modeling. Today there are a lot of standardized software packages which give the possibility not to design the simulation models typical elements (requirements generator, service procedures, etc.) on one's own. However commercially available programs are not oriented to the construction specification and organizational and technological design issues. Adaptation of the packages specialized for transport flow stimulation and business processes is not always effective and convenient. Packages for universal purposes have more features, but labour expenditures for their adaptation to the construction organization issues can be rather significant.

The main direction of modeling problems development in the organizational technological design is the operating time of standardized simulation modules that enables to expand the range of indicated issues. Expanded features of simulation models concerning the obtained results visualization allow to effectively analyze the systems that have not practically taken into account because of their formalization complexity before.

Therefore, modeling in organizational and technological design is the important point in design documentation enhancement and the effective functioning of the construction complex in general.

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DEVELOPING A WEB-BASED 5D SYSTEM CONNECTING COST, SCHEDULE AND 3D MODEL

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ABSTRACT: *BIM, having originated from architecture, is currently being used in civil structures to great effect even though there are few evident examples. Based on BIM technology, this paper presents the method and results of developing a web-based 5D system connecting cost, schedule and 3D model from the cable-stayed bridge. Through this system, the user can easily understand the schedule in relation to specific times and directly extract costs. This system also can manage various data types such as 3D models, documents, photos and drawings for enhanced communication between stakeholders.*

KEYWORDS: *BIM, EVMS, a web-based 5D system, connecting cost-schedule-3D model, cable-stayed bridge*

1. Introduction

The speed of applying IT technology to the construction industry has been very slow. One of the most important reasons is due to a certain level of uncertainty. Generally, the most important method in computerizing processes is standardization. It will have an advantage only if it is unified and repeated. Unpredictable events are very common in civil construction since the primary target is nature. For instance, if we erect two bridges that are exactly the same but in different locations, totally different works will end up happening simultaneously. This is because the conditions of nature are not always the same even if they appear to be on the surface. Also, it is very difficult to predict the weather even with a highly advanced computer. Moreover, applying a new method to civil projects is difficult because civil structures are the huge and wide infrastructures owned by the government and Korean public officers are conservative (I. KANG).

Nevertheless, there have been many strides in construction IT and many results have been gained. The BIM (Building Information Modeling) is the most remarkable of them. The essence of BIM, which is the process of inserting data in a 3D model and utilizing it visually, is integrating all the scattered information. Daelim Industrial Company has developed the system managing cost and schedule data, which is called EVMS (Earned Value Management System). Due to the fact that it consists of text and table, the data is very difficult to understand. So far it has been necessary to develop 5D systems connecting EVMS data along with 3D models in order to easily understand and visualize the data. Various 5D planning programs such as Estimator, Digital Project and Common point, have been developed, but they are not suitable for Korea because the code convention in Korea is totally different from that of other countries (C. CHOI).

In the last year, the 5D system in stand-alone form has been developed (H. KIM *et al*). However, it has frustrated the user because the program has to be installed on each individual computer. Therefore, it is noted that a web-based 5D system is indispensable so that the user can access the system anywhere. Even though there had been some technical problems with the system, these issues have been completely resolved. The methodology and results are presented below.

Target modeling, 2nd Geumgang Bridge and the mechanism of EVMS will first be explained, which will then follow with the detailed process of 3D modeling. Finally, the design of the 5D system will be explained briefly and categorized into a schedule simulation, information management, and cost-schedule management with details of the results.

2. 2nd Geumgang Bridge

The 2nd Geumgang Bridge, which is the target structure, is currently under construction. The construction period is from 2008 to 2011 and it is located at the multifunctional administrative city, i.e., Sejong City in the middle of South Korea. The total length of the bridge is 880m and it contains 6 lanes. It is composed of a cable-stayed bridge section (main span 200m and side span 140m) with a composite steel plate girder, and an approaching section (540m) with a composite narrow steel box girder as shown in Fig. 1. The stiffening girder has an I shaped edge steel girder with a precast concrete deck along with a round and asymmetric pylon which is 100m high. The reason why this bridge has been selected is due to its atypical pylon shape along with the fact that the 3D model was created during the design stage for quantity take-off.

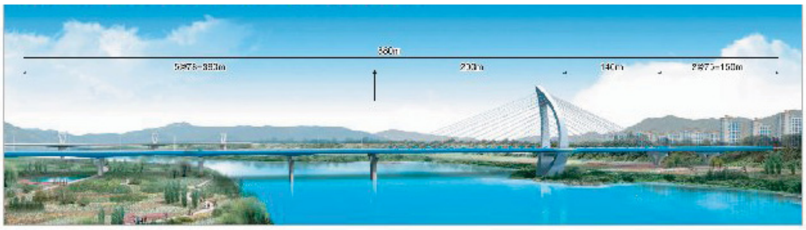

Fig. 1: Overview of 2nd Geumgang bridge

3. EVMS

EVMS is the system of analyzing performance and expecting final project cost and schedule by managing schedule and cost of project and utilizing a structure of standard classifying, based on schedule managing system. In EVMS, standard cost structure, standard schedule structure and standard link structure have already been established.

EVMS is composed of WBS (Work Breakdown Structure) and CBS (Cost Breakdown Structure). WBS at the level of sub-activity is connected with CBS at the 5th level of cost item by matching the table as shown in Fig. 2. The 3D model is connected with WBS at the level of activity, so CBS will be connected automatically with the 3D model. Therefore the 3D model should be divided in order to be adequate for the activity in WBS. The reason why the 3D model is connected with WBS at the level of activity is related to the limitation of representing the detail. In order for the 3D model to show sub-activity, the 3D model has to be split much more minutely. This, however, is nearly impossible because the memory capacity of the computer is limited and cannot reveal all of the information. With the rapid advancement of technology, this issue will soon be resolved.

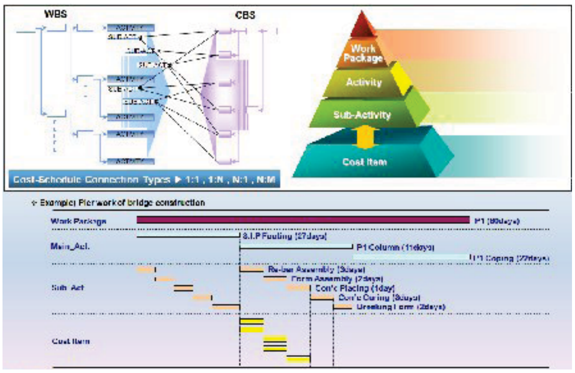

Fig. 2: Structure of EVMS

4. 2nd Geumgang Bridge

Creating 3D Model

The fundamental method is to create a 3D model from conventional 2D drawings. In the process of creating the 3D model, we could correct the error of the 2D drawing and check the complicated shape to see if the delay of schedule was prevented. Initially, it had been made with Revit Structure 2009 as shown in Fig. 3, but it is converted to Microstation V8i format. Some errors were fixed and the detail is enhanced as shown in Fig. 4.

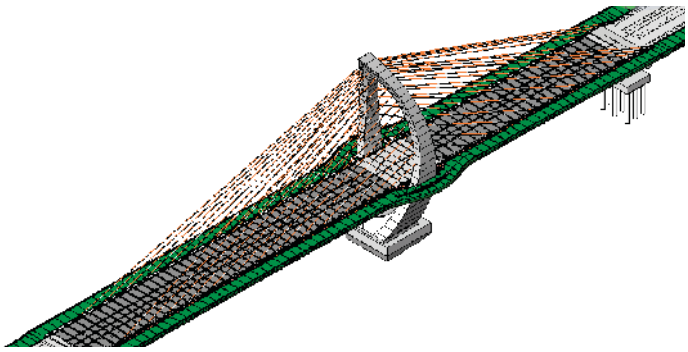

Fig. 3: 3D model created by Revit Structure 2009

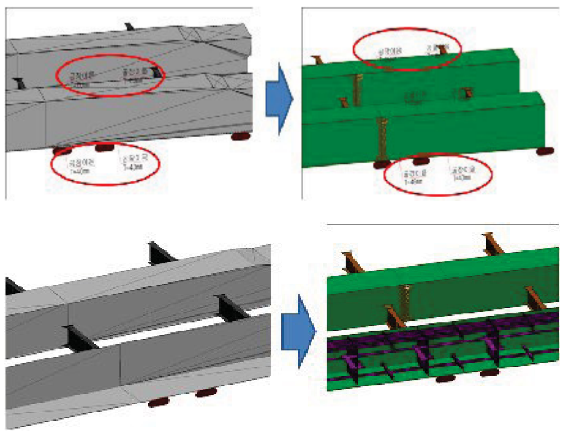

Fig. 4: 3D model updated by Microstation V8i

4.2 Splitting 3D Model

Generally speaking, when the 3D model is created, the level of splitting object, that is the scope of modeling and the detail varies according to objective of applying. For example, if we want to check the interference between members, we will have to do so minutely. On the other hand, if we want to see the schedule process, we will only do so briefly.

In the case of splitting 3D model for a 4D or 5D simulation, the increase in data size is inevitable because of the many objects that come into play. Therefore, we should determine a suitable level of detail while taking into consideration both aim and efficiency. In this case, the suitable level is the activity, considering the capacity of the computer as mentioned earlier. If an activity is given to different objects, then those objects would be perceived as the same activity. Since the aim is to simulate in 3 dimensions connecting EVMS data along with the 3D model, the 3D model is subsequently split according to activity in WBS as shown in Fig. 5. The name of each object should correspond to the WBS code so that the automatic link can be possible.

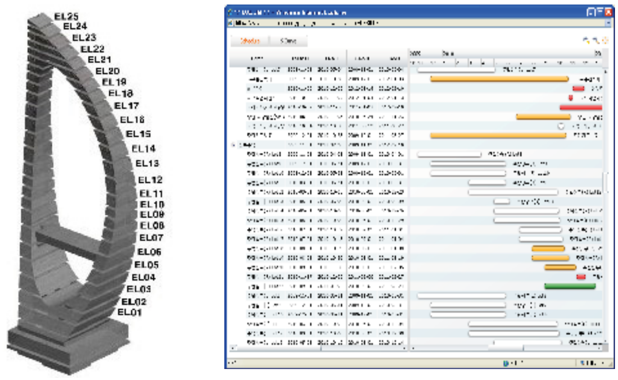

Fig. 5: Splitting 3D model according to activity

4.3 Converting 3D Model

The process of converting the 3D model is necessary in order for it to be published on the web. The very first objective is to reduce the number of objects converted in the 3D model because the number of objects substantially increases after the conversion process. The Virtool program of Dassault, which makes it possible to publish on the web, has a different data structure from the other 3D modeling program such as Microstation or Revit Structure.

The initial number of objects before converting is 158, but the final number after converting is 70,606. Therefore, lots of objects must be classified and grouped as the original form of element so that it maintains the original 158 objects. The second work is smoothing out the surface. When the 3D model is converted, the surface can be distorted and rough, which makes smoothing one by one necessary. The third work is reducing the model size. When it is converted, the surface or volume is broken into the point or line, so the number of elements involved becomes tremendous. By finding unnecessary parts along with deleting and grouping them, the model size can be reduced. The graphic effect can make the 3D model appear realistic. The quality of the 3D model's surface is monotone just after converting it, but it can be changed by texture mapping. After that, the color mapping work starts. It is noted that each mapping should have less than 1 MB in order to publish on the web. These rendering works can make it similar to the real structure. The programming and camera setting can make the interactive results.

5. System Design

5.1 System Architecture

The system is a web-based system of open architecture structures and has the ability of interactive linking with EVMS. The server system has a typical 3-tier structure such as application layer, presentation layer and data access layer. In the user's aspect (application layer), a 3D player compatible with DirectX and OpenGL is used. The presentation layer uses the state-of-the-art technologies such as Flex and Silverlight which are web standard. The cost and schedule data are imported from EVMS through a web service and they are managed in the MS-sql server.

5.2 Linking with EVMS

As mentioned earlier, the automatic linking is realized by mating the name of the 3D object and WBS code in EVMS. When there is a request for data with a user ID and password, EVMS web service supplies cost and schedule data in XML form. Once the schedule data and 3D model are connected, cost is shown automatically, because EVMS has already implemented the link information of cost and schedule.

6. Results From a Web-based 5D System

The system which connects cost, schedule, 3D model and update data has automatically been established. System layout is shown in Fig. 6. Initially, the type of administrative program where data is inserted and modified is planned as stand-alone, but solving technical problems made it possible to complete a web-based system. In this system, all the functions can be performed on the web where authorization varies according to ID.

Fig. 6: System layout

6.1 Schedule Simulation

The system can represent the status of schedule on a specific date or during a specific period. It can also show the running activity (green), the delayed activity (red or orange), the finished activity (white) and the planned activity (grey) as shown in Fig. 7.

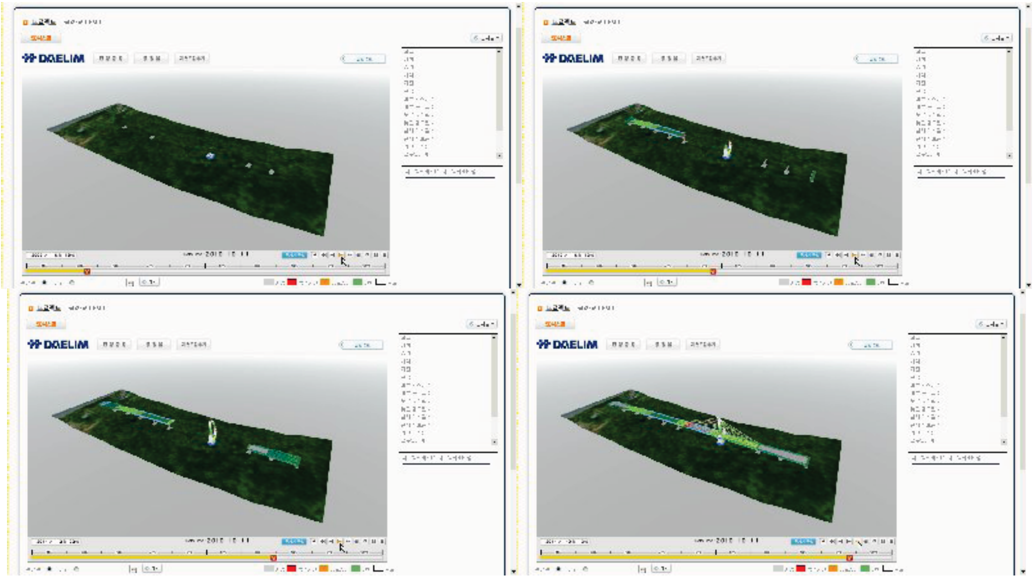

Fig. 7: Schedule simulation

6.2 Information Management

On the specific object, it contains basic schedule data and other various data such as 3D model, photo, document and drawing as shown in Fig. 8. Moreover, the user can enter valuable information such as general project information, material, and volume. The user can open and manage this data from any computer since it is a web-based system.

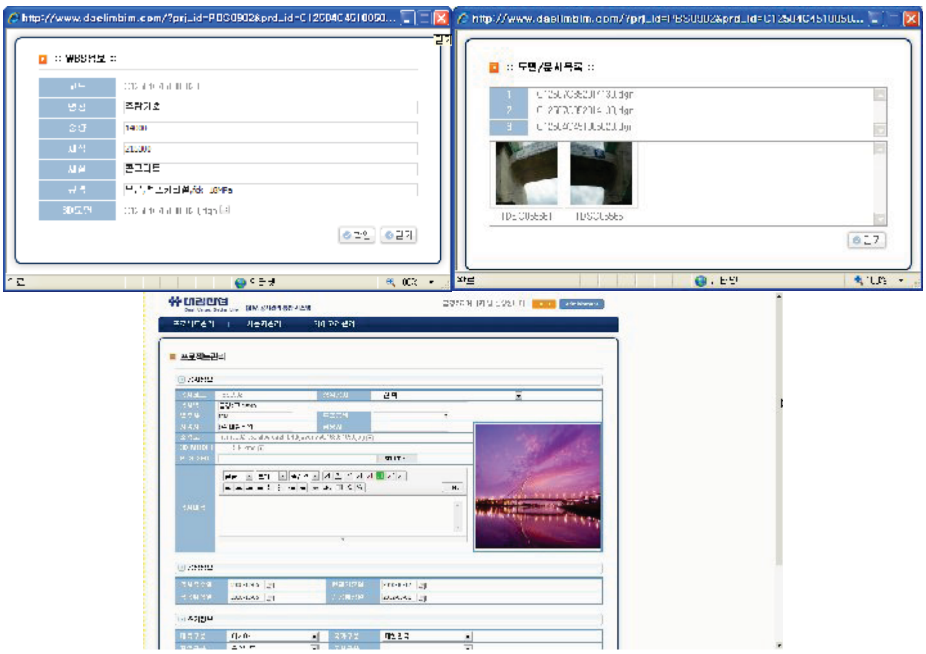

Fig. 8: Information management

6.3 Cost and Schedule Management

It is possible to check real-time cost and schedule information through the Gantt chart and S-curve. The user can select more than one object and the cost information can be shown in list form or MS Excel form as shown in Fig. 9. Before this system is developed, it is very tedious to calculate the cost relating to specific activity. Now they are totally solved and can be represented visually.

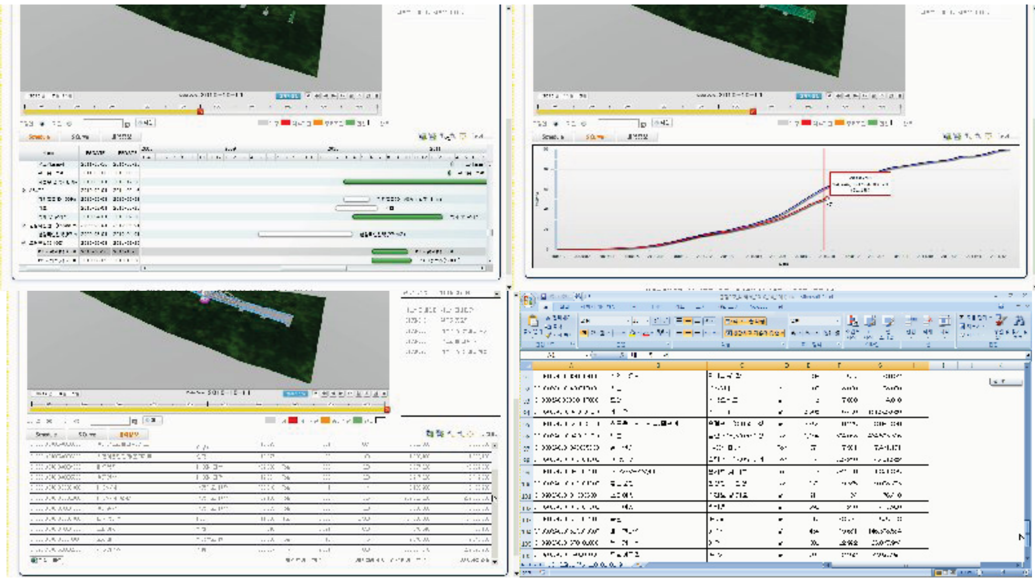

Fig. 9: Cost and schedule management

7. Conclusions

Presented was the method and result of developing a web-based 5D system connecting cost, schedule and 3D model from the 2nd Geumgang bridge. It is adopted the approach of downloading cost and schedule data by web-service, because this phase is researching stage, and the data are connected with 3D model designated by unique ID (WBS code). Through the successful completion of a web-based 5D system, it becomes possible to check the information (drawings, 3D models, documents and photos) at a 3D object, Gantt chart and S-curve in real time.

In the future, communication between stakeholders and the interaction between headquarter and site will be greatly en hanced. Recently, the effectiveness of BIM has been emphasized, but the integration of the overall system and the accuracy necessary for the user is still far-off. Gathering these small efforts, it is thought that BIM will be settled in near future, as the paper drawing became electrical CAD file, which had been considered impossible in 1970s.

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BIM TRAINING COURSE IN CONSTRUCTION UNIVERSITY

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ABSTRACT: *The paper deals with process of introducing building information modeling (BIM) technology into educational process in universities training civil engineers. Since the system of cooperation between universities and construction organizations which existed in Soviet Union has failed in early '90s, many educational institutes have difficulties in providing students with the practical work. As a result – most of the students don't possess necessary professional skills that make it difficult for them to find the proper job after graduation. Today almost all universities are about to turn from the present five years educational system to European one: two-level system (4 years for Bachelor's degree and 2 additional years for Master's degree). That is why both Bachelors and Masters are to be high-qualified specialists who could work not only in native country but also in international projects. The authors consider that BIM is able to improve students' skill and knowledge on construction industry. The role project proposes to use schedule of designing construction documentation for an object and BIM as a tool collecting students of different specialties in order to teach them to communicate, cooperate and evaluate their decisions during designing of common virtual building. Such an organization of educational process is believed to form more competent civil engineers having theoretical knowledge as well as an experience of design and communicative skills. Moreover, the authors expect that information models of existing buildings developed by students could bring attention of potential employers - owners of these buildings as it gives them new opportunities in facility management.*

KEYWORDS: *building information modeling, educational process, role project.*

1. General Characteristics of Learning Process in Construction University

Russian system of training specialists for construction industry underwent a great change for the past two decades. First of all, it concerns the provision of practical field for undergraduates. During the period of planned economy construction organizations had close relations with education institutions, thus providing each student with the necessary experience, enough to start working after graduation. Today construction business and education don't interact with one another in a very intensive way though such cooperation could bring considerable mutual benefits.

Analyzing methods of teaching and organization of studies at universities training specialists for construction industry one should note that the main problem is the lack of proper development of professional competence of students. For example little attention is given to the training skills that aimed at collaboration and interaction in project delivering. Almost all tasks, calculations and term-papers are accomplished by the student himself (after consultation with lecturer). On the one hand, this approach favors student's independence and responsibility for own results but on the other hand it often causes the situation when student takes the ready results of the similar calculation and adopt them. Each task, calculation or term-paper refers to a certain aspect of design or construction process, and relations between them are often omitted to simplify the task. Thus students get knowledge about different objects of design and construction but they don't have the integral idea about the work of design team because every student had to play all roles during his studies.

It is also possible to point out that the latest software tools in the field of design and construction is often used less comparing with foreign colleges and universities.

One of the advanced technology in building design and construction is building information modeling that represents a new approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format [2]. The advantages of the new technology can be effectively applied for educational purposes.

It is obvious that successful career of graduated student depends not only on the theoretical knowledge learnt during the lectures but also on the his/her ability to communicate with all members involved in construction project. Sometimes the absence of practice and fragmental idea of problem domain is a serious obstacle for student's adaptation to the labor-market. Especially if a graduate aims to work in a foreign country where BIM technologies has been already widely in use.

According to [3] learning is a cyclical and iterative process (Fig 1). It starts with the acquisition of knowledge, leading to the application of this new knowledge (practice), which results in evaluation of the practice experience. This brings us full circle and introduce new learning (understanding) from the evaluation that leads to more practice. As understanding increases, the ability to acquire new knowledge will also increase. This development of greater understanding and the ability to apply it can be seen as the development of a skill. The development of a BIM is also cyclical and iterative; the creation of a BIM represents the learning about the project.

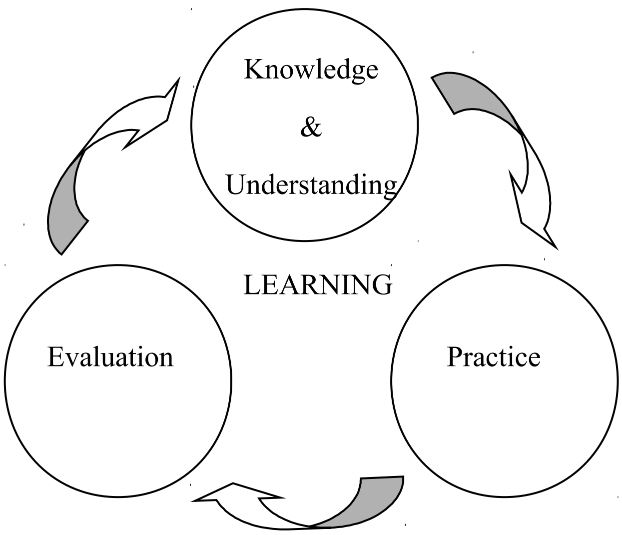

Fig. 1: Learning process

2. Role Game As the Way To Introduce BIM Training Course

BIM training course in the form of role project can be regarded as the means to increase quality of educational process and make it more adequate for real conditions. This course is supposed to gather students of different specialties in order to develop common project within a limited period of time. Today this approach is not used in Russian construction universities.

The main idea is that to divide the total number of the last year students of all specialties into several teams consisting of future architects, structure engineers, plumbing engineers, electrical engineers, estimators and other specialists. Number of members in each team may vary depending on the scale of the project. At the same time a group of consultants and mentors is formed and assigned to a team. Each team is given a schedule of designing construction documentation for a particular object (Table 1). The schedule represents the table showing the sequence of elementary design operations and the role of specialist within the process. Thus the team should first of all take into account the schedule to plan the co-operation between its members.

Column 'Duration' may contain number of days specified by the consultants and column "Date" should fix the real date when operation is done. The role of specialists (specialists are marked by following abbreviations: ENG – General Engineer; GL - General Layout; ARC – Architecture; STR - Structure Engineer; TECH - Mechanical Engineer; VEN - Ventilation Engineer; PLM - Plumbing Engineer; EL - Electrical Engineer; EST – Estimator) is denoted by "o" and "+" where "o" shows engineer responsible for data (document) issue, and "+" - engineer responsible for acceptance of data (documentation). Column "Notice" is left for consultants and their notes. The schedules like the given one can be used as a task for diploma paper or as an obligatory part of diploma paper.

When BIM is developed, it is brought up for a discussion (assessment) to a special committee consisting of university's professors and lecturers which decides whether the model is full, adequate and accomplished under determined codes and guidelines. The information model can be directed for further development or correction of revealed defects.

Team members have to develop collaboration skills and learn to work with outside consultant. Collaboration is a fundamental concept to the whole BIM process. It helps a learning team to become a team, overcome obstacles, and make progress. It will be important to have a team that can deal with problems by collaborating to generate possible solutions.

Table 1: Example of schedule of designing construction documentation for multistorey block of flats.

Operation	Duration (days)	Date	ENG	GL	ARC	STR	MEC	VEN	PLM	EL	EST	Notice
STAGE I												
Task for design development			o	+	+	+	+	+	+	+	+	
Preliminary floor plans, general layout				+	o	+	+	+	+	+		
Reverse task *(-Technological plans, staff, engineering facilities, general structural decisions)*			o	+	+	o	o	o	o	o		
General layout scheme, vertical layout scheme				o	+							
Architectural decisions			+	o	o							
STAGE II												
Task for design			o	+	+	+	+	+	+	+		
Plans: basement, floors, roofing, well; sections, facades.				+	o	+	+	+	+	+		
Layout drawing				o	+	+		+	+	+		
Vertical layout				o	+	+		+	+	+		
Technological plans, floor loads						+	o	+	+	+		
Trench bottom mark			+	+		o						
Foundation			+	+		o					+	
STAGE III												
Basement – designing of engineering systems, holes, openings.					+	+		o	o	o		
Basement – structure					+	o						
Basement – public quarters plans					o		+					
Basement - walls, pillars, columns, ceiling			+			o					+	
Basement - floors, sections, details			+		o						+	
1st floor – designing of engineering systems, holes, openings.					+	+		o	o	o		
Final plans: basement, floors, equipment, roofs, wells; sections, facades.				+	o	+	+	+	+	+		
1st floor - walls, pillars, columns, ceiling					+	o						
Equipment, loads					+		o	+	+	+		
Outdoor entrance				+	o	+		+	+			
General and vertical layouts – defined according to departments' tasks				o	+	+		+	+	+		
1st floor - , sections, details, facades			+		o						+	
Openings and holes: all floors					+	+		o	o	o		
Openings and holes: technical floor and roof					+	+		o	o	o		
Loads specification								o	o	+		
STAGE IV												
Details, sections, elevations					o	+						
Technological decisions			+				o				+	
Building structures (Part 1)			+			o					+	
Architectural decisions (Part 1)			+		o						+	
Building structures (Part 2)			+			o					+	
Architectural decisions (Part 2)			+		o						+	
STAGE V												
Engineering systems			+					o	o	o	+	
General layout (including development of nearby area)			+	o							+	
Estimation			+								o	
Project delivery			o		o	o	o					

In fact the advantage of BIM is that it provide simulation of construction process in virtual environment and that can be very informative, visual and comprehensive idea about construction process as well as about all preconstruction work.

If we speak about introduction of BIM training course we should mention the possible obstacles arising in this process. Some of them can be related to one (or more) of the following problems: lack of understanding the process (conceptual issues), inability to use the required tools (technical issues), circumstances (environmental issues).

Conceptual problems are generally addressed with knowledge about BIM process. Hardly one can find theoretical BIM course being lectured today in university. However theoretical background is of important for a professional. The students should realize the difference between traditional CAD technology and BIM or the difference between surface modeling and parametric one.

The problem of inability to use the required tool can be solved by teaching proper software tools to students at the second and third years of studies. It is done because students learn general subjects at the first year. Bachelor program lasts 4 years and master – 5 years. So before a student starts developing his degree work at the last year he will know the theory of his subject and he will be able to use the necessary tool to apply his knowledge in virtual environment.

There are some circumstances that indirectly may influence on the team work at the project. These are: qualification of lecturers, mentors and consultants; the space in which the learning takes place; the availability of means of communication etc.

In any case when decided to introduce BIM the authority of university should investigate the existing level of technical and software equipment. Because the task is to prepare the ground for the future continuous process of project designing. Otherwise there will be a risk to break up the educational process and lose too much time.

There are several keys aspects in successful introduction of BIM in construction university. One of them is that the use of real projects makes educational exercise much more meaningful. Whether the model is being designed (as in architectural or engineering studios) or built from the design drawings, the realty factor of an exercise can have many positive effects. The use of the existing information of actual projects also makes the challenges of the simulation realistic. Solving problems that are too simple will not help much when it is time to handle reality.

The building information model created by the students may be useful for many purposes. In fact, more and more owners are aware about BIM technology and models and would like to apply it in facility management. But they don't know how to get such model and how it functions. In this case graduates could present the owner (potential employer) their results of the work done within role project and explain basic moments about information model, its advantages and possibilities. It is a challenge to model already existing project and in this case the cooperation between the real owner and the team will motivate the latter to do its best. Thus new kind of service can appear soon, service when civil engineers create BIM for existing building and maintain it in proper condition.

3. Conclusions

Russian universities have already started passing to a new form of educational system: the new four-year Bachelor's degree which is followed by two-year Master's degree (comparing with five- or six-year engineer training). And that should enable students to learn fundamental basis of construction science as well as to acquire practical skills within shorter period of time in order to be employed after graduation.

Thus educational process is to go along with the technological progress of the industry. Today it is BIM that is new technology of construction and it's impossible to imagine BIM without BIM specialists: BIM Modeler, BIM Analyst, BIM Facilitator, BIM Manager and other [1].

Role project is thought to be effective tool chosen to simulate construction of the project in virtual environment. It is believed to allow forming students' skills of collaborative work in complex project as well as teaching them latest information technologies. Another advantage of BIM is that it can also show weak spots in construction process execution and that will allow student to avoid some mistakes in the future.

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REAL-TIME 3D IMMERSIVE VISUALIZATION TECHNOLOGY FOR CONSTRUCTION RESOURCE PLANNING AND MONITORING

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ABSTRACT: *Data visualization and situational awareness through real-time virtual environments can have a significant impact on how workers successfully and safely complete construction projects. Data of construction resources, like personnel, equipment, and materials is vast, however, the effort to collect and analyze it automatically has not been a priority in the construction industry. Although some remote sensing and intelligent data processing technologies exist to supplement manual data recording and interpretation, very few data visualization tools in construction exist that allow visualizing dynamic resource data in a field-realistic three-dimensional immersive reality environment in or near real-time. The motivation of this paper is to acknowledge state-of-the-art technology in real-time data collection and visualization in construction safety applications. A technology-based framework is presented that implements a real-time remote sensing technology for resource location tracking and a real-time data visualization tool. Both are integrated to visualize the situational awareness and safety performance of construction equipment operators and workers on the ground. Results are presented in the context of two significant construction safety applications: (1) Real-time construction safety performance monitoring, and (2) real-time construction safety data visualization.*

KEYWORDS: *3D; decision making; real-time data sensing, modeling, and visualization; real-time pro-active safety; 3D immersive virtual reality.*

1. Introduction

The distributed nature of construction project information and the presence of multiple teams performing on site are well known characteristics of a typical construction project. Communication of essential information among construction project stakeholders is considered a key for successful construction engineering and management. Traditionally, an enormous amount of site information has been communicated among project team members by means of paper-based documents including two-dimensional drawings or verbal communication. A significant deficiency in the traditional information delivery process has been that the project team is not always in the position to make rapid and correct decisions because of unavailable or insufficient information.

With the purpose of making timely and accurate decision of the construction process at multiple timescales and for multiple entities, a deeper understanding of construction activity information can be provided in real-time and visually to any project stakeholder. A more effective use of the gathered real-time information would then generate new knowledge that leads project stakeholder to make faster and safer decisions on-site or from a remote location.

Most of the important information of construction activities such as the location of the construction resources (personnel, equipment and materials), their inter-relationships and temporal information on specific work tasks are currently monitored and recorded by manual observation. Such observation tasks require experienced observers but many observations remain error prone as they are very labor intensive, subjective. Moreover, manual observations are made through the eyes of the observer, and the particular perspective cannot be shared with a project team in or close real-time. This can become a bottleneck for fast and accurate safety decision making on a dynamic construction jobsite.

Virtual reality (VR) is a method of visualization aligning the virtual objects with the real world. Many applications of VR technology have been found in building science covering both project design and construction operation levels. Immersive VR systems also have wide applications in practice and education of architects, engineers and contractors dealing with the design and construction of buildings. The main reason of its rising implementation is that immersive VR has the unique capability of giving users a sense of presence and scale, as if they were observing a realistic world by immersing the user in a computer generated synthetic environment. VR learning and training offers an active learning experience where the user is in control and is required to deliberate proper actions. VR also facilitates the understanding of complex construction process by the interaction with VR (Setareh et al. 2005).

Tracking and visualizing dynamic resource data in a field-realistic virtual environment in real time has other additional benefits to the project team (Cheng and Teizer 2010). For instance, the safety behavior of a worker can get better once they perceive the risks they work in easier. Such risks often have the origin in the motivation to achieve higher levels of productivity that pushes workers to work 'near the edge' and beyond the zone of control or recovery (Mitropoulos et al. 2005). One alternative to prevent such situations, is training construction workers for safety at the front-end planning phase and before the executing work tasks start.

This paper addresses one of the key research challenges in real-time pro-active construction safety: Gathering and processing construction resource data in real-time and visualizing only the most relevant safety information to the user in real-time. Remote sensing technology and visualization technologies are introduced that monitor, record, and visualize safety critical data of construction resources (personnel, equipment, and materials) in real-time for realistic and rapid virtual immersive visualization and simulation environments.

2. Background

Many efforts tried to implement virtual environments for the purpose of visualizing architectural designs and facilitating building construction and project management level. Maldovan and Messner (2006) investigated the use of virtual mockups to replace existing physical models by developing a virtual reality (VR) environment for a courthouse project. Fernandes and Raja (2006) conducted a study describing the barriers that impact the practical implementation of VR, such as management support, degree of business competition, coordination of design resources and participation of end users. Messner and Horman (2003) developed an immersive large scale VR projection system for students in the architectural engineering program. Kalisperis et al. (2002) and Moloney and Amor (2003) also used VR applications in an architectural design studio to coordinate and critique student work within a collaborative virtual environment (CVE). Lipman and Reed (2000) constructed a Virtual Reality Modeling Language (VRML) representation of steel structure and construction equipment with online project information access.

Visualization technology has been widely applied construction management and practice. Virtual construction allows stakeholders to detect and inspect construction problems early in the design phase and enables contractors to manage projects more efficiently (Chau and Anson 2003, McKinney and Fischer 1998, Koo and Fischer 2000, Huang and Tory 2009, and Bansal and Pal 2008). Most of the research available focused on cost, scheduling and the extent of architectural design. VR technologies has since been implemented successfully and resulted in significant cost savings in particular when applied in complex projects. To date, there is little VR research focusing on factors such as real-time pro-active safety and productivity monitoring and analysis at the detailed construction task level. The PI has attended the Real-time Location Tracking Workshop at the Worcester Polytechnic Institute (WPI), a workshop that focuses on real-time location tracking and (recently) visualization technology for search and rescue crews. Two major industry consortia have been formed in 2008 to address the real-time indoor tracking problem of firefighters. No consortia have so far addressed adequate real-time visualization of data. A clear agenda for real-time data visualization is missing.

As the search and rescue efforts operate in similarly harsh environment as construction workers do, real-time safety hazard recognition, reporting, and visualization has become an important element which prompted researchers to investigate at the earliest possible stage in the process (Furnham 1998). Traditionally, safety hazard identification in construction has been using a combination of site drawings and project schedules that were issued by consultants or through visual site inspections. However, these drawings were mostly in 2D making a 3D understanding of the environment a difficult task for safety managers (Hadikusumo and Rowlinson, 2002). Their application is not very common on the construction task level since most VR models are based on simulated data or prerecorded data and can not represent or reproduce the immersive environment in real time. In addition, existing VR tools require expert knowledge to handle and customize the intensive graphical and dynamic characteristics of construction task modeling (Issa et al. 2003). Virtual reality on the construction operation level focuses on resource level (personnel, equipment, material, space, time). Kamat and Martinez (2003) formalized a description language to facilitate automated communication between simulated dynamic construction scenarios and computer graphic facilities and to visualize construction operations in 3D virtual worlds. Kamat and Martinez (2005) also developed dynamic 3D visualization and simulation of articulated construction equipment, such as crane and excavator, by using principles of forward and inverse kinematics. Their research proposed an approach to achieve smooth, continuous motion of virtual construction resources based on discrete and simulated information. Recent research investigated the generic and scalable techniques to accurately represent 3D motion paths in dynamic animation of operations simulated using discrete-event simulation by using the VITASCOPE visualization system (Kamat and Martinez 2008). Rekapalli and Martinez (2008) presented accurate and high-speed animation of simulated models.

Apart from construction industry, VR and VE have already been widely used in other engineering fields. Santamaria and Opdenbosch (2002) introduced an application of VR tools that integrated near-real-time visualization with publish and subscribe mechanisms to achieve remote monitoring and control of dynamic objects in underwater construction and maintenance operations. Fernandes and Raja (2003) created a virtual training system as an integrated system consisting of a training visualization suite, an interface model, and instruction module. Fully immersive training environments for the manufacturing industry have received some initial attention.

3. Methodology

The main objective of this paper is to increase the awareness of a project team and involved parties so that they can make more informed decisions in less time and at lower cost. In order to accomplish this objective, one solution is to implement a virtual reality tool that integrates real-time tracking and visualization with a mechanism to achieve remote monitoring of dynamic construction process in a virtual job site. The virtual world model has to accurately simulate the real job site and it must allow the operators and users to observe and interact with the real world indirectly through a virtual environment based on the virtual model.

This paper integrates the emerging sensing technology and visualization system to produce accurate and timely information for distributed decision makers and multiple users. The solution consists of four central phases: Data Collection, Data Processing, Visualization, Decision Making and Training (see Figure 1).

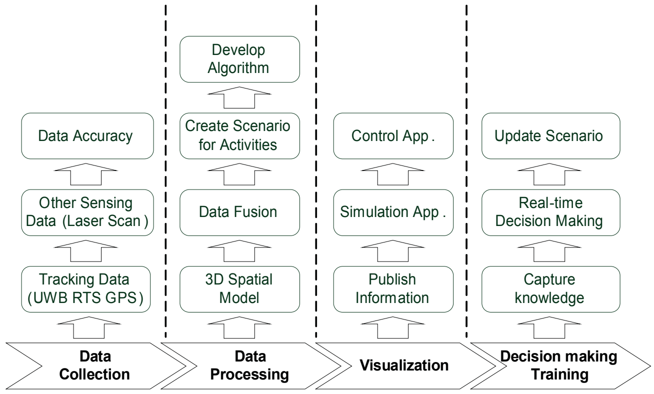

Fig. 1: Flowchart of real-time visualization

Since different types of information are required by various parties of stakeholders, selections of sensing technologies can serve their demands. The raw data that always includes spatial and temporal attributes collected by the sensor must be processed and form relevant information before it is delivered to decision maker. Especially, in some construction applications such as safety and health practice, a real-time feedback is necessary, which requires real-time data acquisition and processing. Furthermore, the appropriate knowledge learnt from the fast decision making process is stored for long-term memory. It can be retrieved and reproduced for the purpose of training and education. A real-time visualization phase is integrated after the data processing phase which has a function of building a rich and realistic virtual reality model that can visualize the extracted information. With the help of robust data distribution, stakeholders are able to make their decision in interactive visualization of three-dimensional (3D) scenes.

3.1 Real-time tracking

There is an immense interest and potential in systems that provide users the location of project critical resources (workforce, equipment, material). Knowing the location of construction resources (workers, equipment and material), and identifying and measuring the status of work tasks helps to improve the project performance. Varieties of real-time sensing technologies such as UWB, GPS and vision tracking can be implemented to collect 3D/4D (spatial and temporary) data. However, in most construction tasks, the data is scattered across several systems, many of which are isolated from each other. High deviated choices of sensor technologies make the data consolidation and data fusion a real challenge. One alternative is to apply a protocol that adapt to any data stream. Another alternative is to constrain the input data into a uniformed data pattern even if it comes from different sources, including databases. The research scope of this paper only focuses on one data source from a specific tracking technology. Although any of the tracking technologies could have been selected to monitor the trajectories of construction resources, a technology that is capable of studying the location of workers, equipment, and materials at the same time and at high update rates was selected. Preference was mainly given to a technology that is small in size and can be worn by workers, is rugged and reliable enough to withstand the harsh construction environment and is capable of accurately and precisely recording the activities that are associated to the selected work task, material handling.

In addition, most of the sensor raw data is collected in combination of noise and real-time tracking technologies have not been widely applied in construction site. The performance of the technology is impacted by the complex environment of the jobsite. Therefore, preliminary data accuracy check must be conducted before it is used to retrieve relevant information about construction resources. Data noises and errors are corrected through the use of filtering algorithms.

3.2 Virtual reality simulation

A virtual reality world applied in this paper uses an efficient data structure termed world data model, which consists of a list of entities with properties designed to represent their real-world counterparts. The entities are the basic element of the virtual world, which involves scene, surfaces, light, objects, cameras, relations and labels. The scene of visualization tools is a collect of interfaces and modular components that define the elements of a virtual environment, such as surface, static and dynamic objects, cameras, lights and indicators. The surface and static objects are reproduced based on the application of survey technologies. Laser scanning is used in the survey of the construction site. The point clouds collected by the survey instrument in the first stage are used for triangle mesh and the surface is therefore represented by rendered polygons.

The survey of site surface and static objects are accomplished by a set of scans, and each scan will create an individual scan world which contains a large number of point clouds. Since every scan world has unique coordinate system, a registration process is implemented which connects a set of scan worlds into a uniformed coordination as a project's scan world. This integration is derived by a set of constraints, which are pairs of equivalent tie-points or overlapping point clouds that exist in two scan worlds. The registration process computes the optimal overall alignment transformations for each component scan world in the registration such that the constraints are matched as closely as possible. However, the registered project's scan world still contains several point clouds from scan worlds, even though the point clouds are coordinated, triangle meshes cannot be created across different point clouds. Therefore, the point clouds from each scan are unified into one single point clouds through unification process. In addition, some features on the surface such as edges and corners have to be preserved when a triangle mesh is created. Therefore, several polylines termed "breakline" are implemented to represent a curb on the edge between different surfaces (See figure 2). The breaklines assist in the generation and decimation of the mesh in that they will preserve the geometric features. Based on specified breaklines and unified point clouds, a TIN mesh is generated where there are no overlapping triangles with respect to the vertical direction. As a sequence, a surface model is produced by rendering the TIN mesh created from the point clouds.

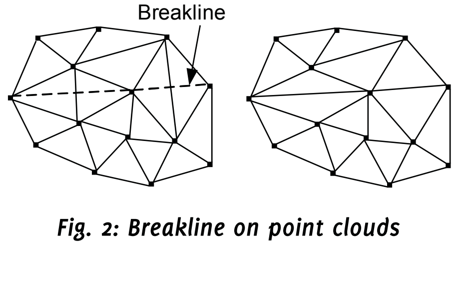

Fig. 2: Breakline on point clouds

As another part of the virtual environment, the light is not always a real-world counterpart in most scenarios, but simulated directional, spot and conical light are widely implemented to represent the concept of light resource in VR tools. Objects are present using CAD geometry or basic shapes (e.g., cubes, cylinders, spheres, cones, etc.). Complex objects are represented by using level of details (LODs), whose definition consists of several geometry descriptions with different levels of detail. Therefore they are sensitive to proximity of the viewing camera.

The properties of dynamic objects are updated through data server which receives real-time data from the sensing technology. The data is bond to the various properties of objects to be visualized. However, most relevant information is not explicitly defined in the original data source. Location-characteristic information of tracking data from construction resources (people, equipment, material) including velocity, orientation, proximity of two or more resources, and the frequency that resources interact with each other, is derived from location tracking data. The velocity vector (direction, orientation, and speed) of resources is calculated through the comparison of its current and previous location. The orientation of object is determined via multiple UWB tags placed on the machine(s). One example is computing the distance between several dynamic objects (workforce, equipment, materials), and simulating a machine and its subcomponents. Compared to raw data, the derived information is more valuable for the stakeholders to make effective decision. Specific algorithm oriented to certain user objective is developed in analytical applications.

The camera module defines various viewing points in the scene that could responds to several input devices. The virtual camera can be attached to any moving objects to provide multiple vantage points. Relations are applied to connect entities in the scene, which represent the interdependency between elements existing in the real world. For example, the distance between two objects or a projection distance between an object and a surface. Figure 3 shows the architecture of real-time tracking and visualization system.

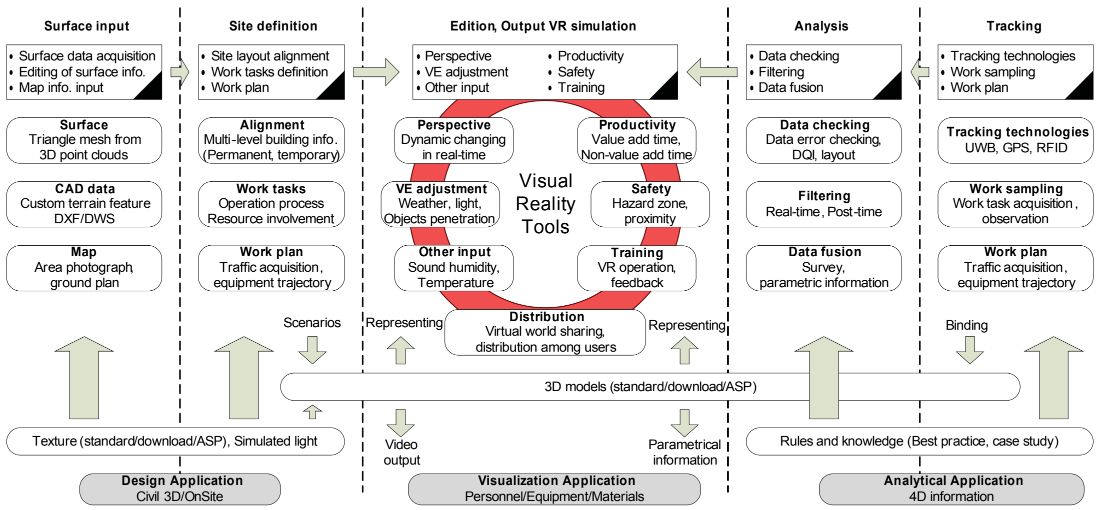

Fig. 3: Architecture of real-time tracking and visualization

3.3 Real-time Data Distribution

In order to satisfy the information requirement of distributed project team, relevant information must be delivered not only to the local server but also must be visualized in a remote 3D viewer. It requires that the data server of visualization system not only has mechanism of data subscribing and publishing but also has capability to take advantage of the current internet and intranet infrastructure. Figure 4 shows the architecture of data collection and distribution, data processing and visualization. As the user defined three dimensional virtual world is created from the local server, it is shared by multiple users via internet or intranet access.

An elaborate world model includes complex static structures and dynamic objects, such as buildings, equipments, materials and personnel, which assist and improve the perception and understanding of the job site. When the elements of the virtual world are linked with real-time sensor, update of sensing data from instruments and positioning sensors is made available by using a subscribing mechanism and a local real-time data server. The real-time data server is responsible for maintaining an accurate representation of all the dynamic and static elements that compose the job site scene. Relevant information for decision maker such as localization, distance, velocity, acceleration and orientation is retrieved by local server. The server saves the job-site scene using an efficient data structure, which consists of a list of entities (surfaces, objects, light, camera, relations, etc.) with their properties designed to represent the counterpart in the real world.

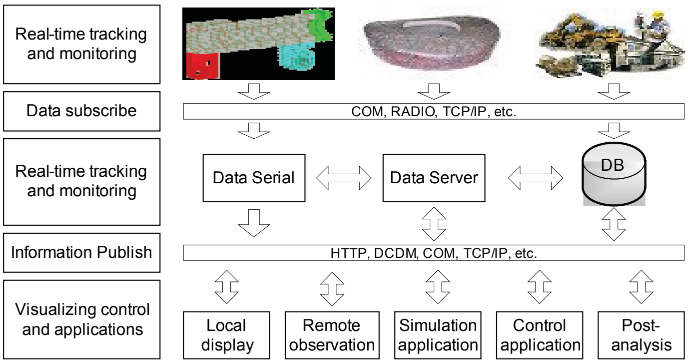

Fig. 4: Architecture of data and world model distribution

The publishing and subscribing mechanism allows other application or data collectors to synchronize the update and query information about the virtual world model. Users with Internet or intranet access can subscribe to any real-time data field being published and receive updates each time the information changes, allowing them to monitor and log the events of the job into database at the same time they are taking place.

The information is published to the server and distributed to the multiple user at both local and remote location in real-time through the data visualization module to facilitate fast and corrected decision making. The application allows the operators and users to observe and interact with the real world model through the virtual environment that increases the awareness of distributed project team. Moreover, the users are also able to track the feedback of their decision of the project in remote location in real-time based the system.

The virtual reality system has also applied as training and teaching tools. Real-time visualization helps the trainees and students gain an intuitive understanding of job site complexity. Since all the sensing data published to the server is logged, a reconstruction of the working activities and operations can be accomplished in post-time. The data is logged with time stamp that can be used during the playback to monitor the training progress comparing with event log system. In combination of the feedback from training facility, the training scenario created before is therefore promoted and updated.

4. Experiments and Results

Several experiments have been conducted to test the applicability of implementing real-time data collection and visualization technology in construction operation. The experiments are in particular concentrated on relations between working resources. The first experiment illustrates a common scenario that worker is approaching to heave equipment and elevated loads. The second scenario reproduces an ironworker training procedure based on real-time data collection.

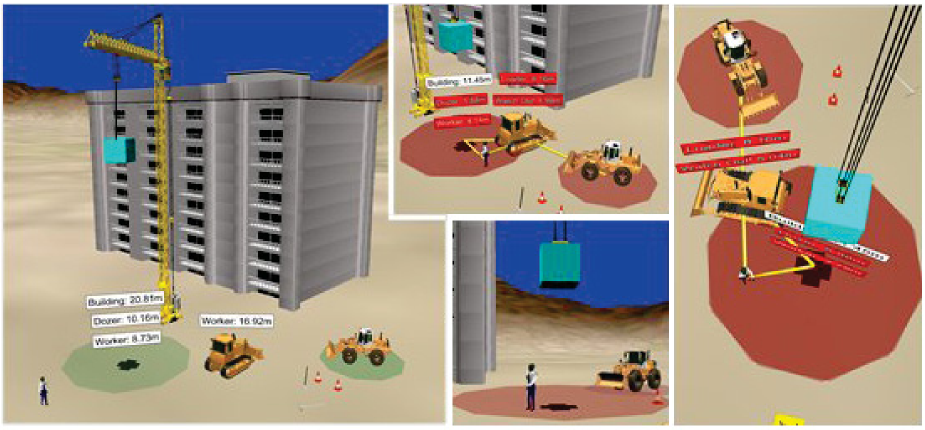

Fig. 5: Visualization of close calls using simulated data

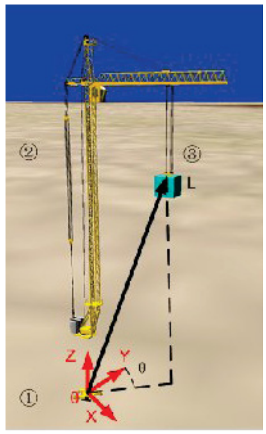

Fig. 6: Simulation of the crane activities

4.1 Simulation of Close-calls

Research indicates that the number of accidents and incidents is distributed as a pyramid, with major accident causing fatalities at the top, minor accidents rising injury in the second top, observation of near-miss at the broad bottom. Statistics indicates one fatality occurs on the construction site is always accompanied with 3000 near misses and all near-misses have the potential for more serious sequence. However, majority of the near misses are not even observed by the safety inspector or realized by workers. An interactive 3D virtual environment actually facilitates the inspection of operations from dynamic perspective so that potential near misses can be forecast and avoided in an effective way by a rapid decision making. Figure 5 illustrates the creation of virtual world and it also shows a simulation of several near-miss scenarios which can be commonly witnessed on the site.

The scene consists of five major objects, a dozer, a loader, a worker, a crane with load and a building. The spatial data is subscribed to the server and the processed information is published into the 3D viewer. Two preliminary defined dangerous zones are denoted by green circles around the static loader and projected from the load onto the ground. The distance between each pair of entities is computed automatically from the spatial data. In this scenario, approaching distance is considered to be a significant estimation of the risky near-miss. The size of dangerous zones can be defined according to safety guideline and OSHA standards. Both circular regions maintain in green when all the other resources (worker, equipment, and materials) are far apart from the center of the dangerous region. Regions switch to red when other tracked objects are approaching below the threshold defined by users. Figure 3 shows several cases that human or the machines enter others' dangerous zone and the distance between them are displayed and labeled.

The trajectory of the dozer and human can be directly extracted from data, but the headings of the dozer and worker are determined by their tangential direction along the trajectories which changes via the time and must be calibrate by at least two spatial spots along the path. In order to determine the heading of the dynamic object, two sensors are mounted on the target aligned with its facing direction. Both sensors collected their location data simultaneously and therefore the heading is calculated by the tangential angle of the vector formed by tow location records.

Another challenge in this model is to simulate the activity of the tower crane, which involves two degrees of freedom: the heading of the crane arm along the base axis and the elevating of the load. Since the sensor data can only provide absolute spatial information, same as the derivative of worker's heading, multiple sensors are necessary. The crane structure is break down into three major subcomponents (Figure 6), crane base, crane boom and the pulley attaching on the boom and connecting to the hook.

4.2 Visualization of active construction pit

In the previous example, the virtual world model is tested based on the simulated data. In this example, an experiment and its result are being introduced to illustrate the visualization on real-time data collected by sensing technology. The experiment was conducted in an active construction pit, which occupied a working area of approximately 1,800 m¬2¬. A three-dimensional laser scan was accomplished to document the as-built conditions. The registered point clouds were implemented to create the virtual scene. Figure 7 shows the captures of the same jobsite by camera, laser scan and virtual world mode.

An active Radio Frequency Identification (RFID) technology called Ultra Wideband (UWB) was used to track the resources. The position of a rebar crew and the activities of a mobile crane were tracked and monitored by the UWB technology. During the experiment, each worker from the rebar crew was outfitted with a UWB tag, which collected spatio-temporal data and subscribed the data to the server. Construction task related information such as position, speed, heading and so on was therefore calculated by the server. The processed information was then published to the virtual environment, and banded to the corresponding 3D model with unique object ID. The activities of the mobile crane were captured by multiple UWB tags. Four tags were mounted on the stationary supportive peers; one UWB tag was mounted on the structure frame of the crane cabin; and another UWB tag was mounted on the crane hook. The heading of the crane boom was therefore calculated based on the location of the crane hook projected on the horizontal plane with the reference of the 2D position of the stationary supportive peers (see Figure 8).

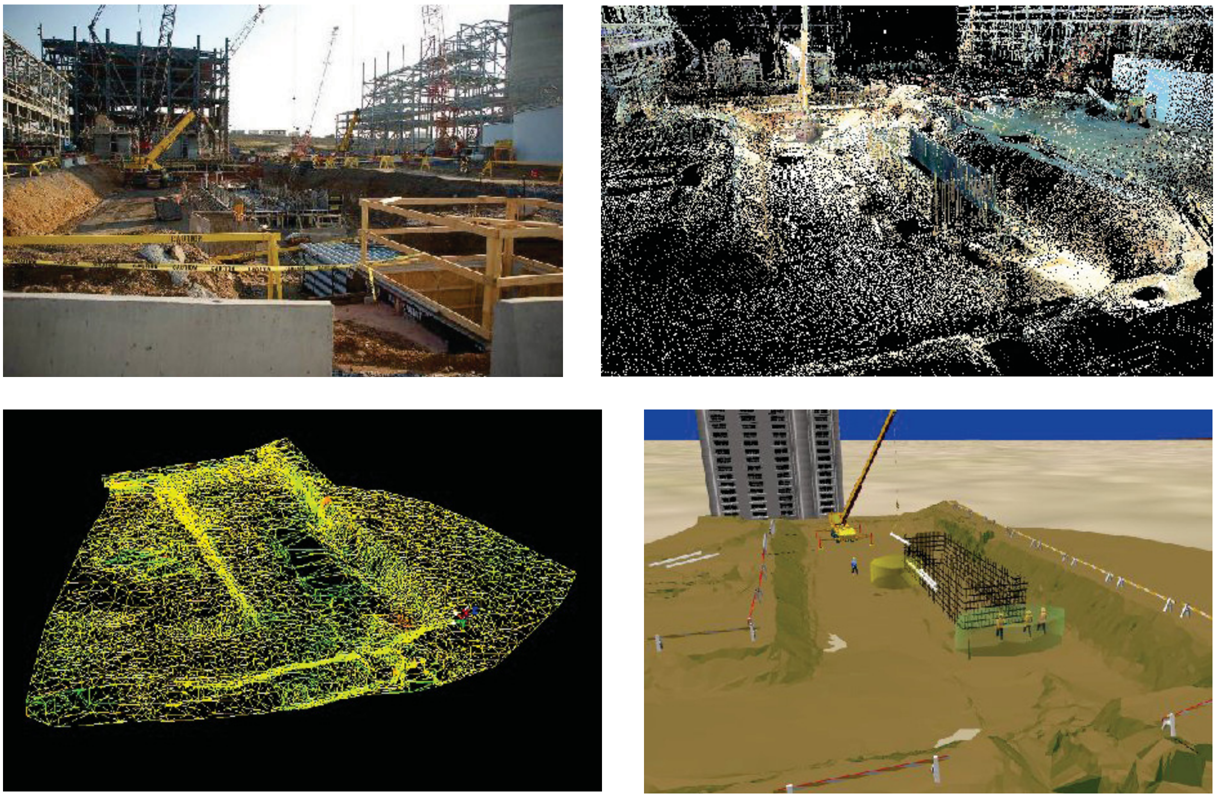

Fig. 7: Construction pit in photo, laser scan point clouds, triangle meshes and virtual model

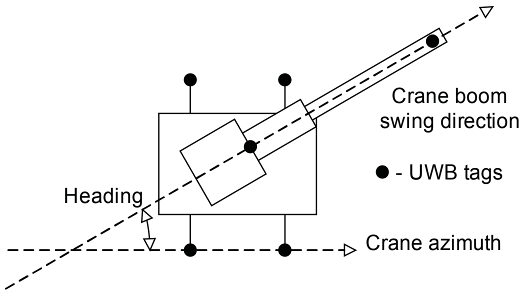

Fig. 8: Determination of the crane boom's heading

For the purpose of the automatically observe the safety and productivity related working activities, two zones were illustrated in the virtual reality model (see figure 9a). A safety practice related warning zone represented by a yellow cylinder was created under the crane load. Meanwhile, several relationships between workers and crane load were established based on the tracking data. The distance between the dynamic objects were computed in real-time and labeled in the virtual world. Once a worker invaded into the safety zone while the crane was swinging with load, a visual warning will be given and the color of the safety zone turns from yellow to red. Besides, the productivity related activities can be also observed through the virtual world model. A stationary work area linked to specific the work task was created by a green cylinder. Relationships were established to compute the distance of a worker to the specific work area. Being apart from the work area indicates the non-value added time to the specific task. Figure 9b showed the visibility issue raised by the crane boom of the same working activity from the plan view. The blind spot from the crane operator's perspective was illustrated by the dark area. After the tracking data was published to the virtual world, it can be noticed that a rebar worker was working in the blind spot area of the crane operator, and two workers who were close to the load were visible to the crane operator when the crane boom was swinging. The approximate blind spot angular ratio of the crane operator in this frame was 31%.

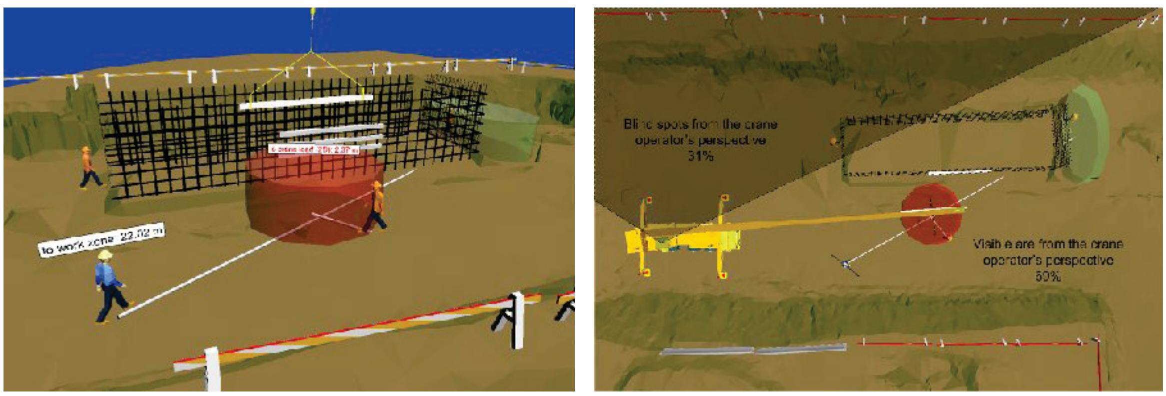

Fig. 9: (a) Visualization of work activities, and (b) blind spots area from the crane operator's perspective

5. Conclusions

Although the VR technology has already been widely used on construction design stage in recent decades, limited research has covered the application of VR technology in combination with emerging sensing technology on a construction operation level. A mechanism of implementing real-time data collection and visualization technology in construction industry has been developed and was tested in this paper. The real-time tracking and visualization system contains real-time data collection, data processing, visualization and applications on training. The relevant information for the project team is derived from collected data and visualized for support information. The information represents the state of construction resources and their inter-relations can be transmitted to other distributed decision makers. Stakeholders are able to inspect and make fast decision based on real-time information in an interactive virtual three-dimensional (3D) environment and track the output of any changes in the same manner. Several experiments, including data collection with spatial imaging and wireless real-time location tracking of construction resources (personnel, equipment, and materials) were presented. These show that real-time 3D immersive data visualization has applications in the construction field. Likely areas that will benefit from this technological approach are interactive construction information data sharing, productivity monitoring, and safety control.

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SELFRUNNING SOFTWARE ACCESS FOR THE EXPLORATION OF VIRTUALLY RECONSTRUCTED SYNAGOGUES

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ABSTRACT: *This contribution focuses on the so-called "Virtual Building Explorer (VBE)", an adapted game-engine, which is now being used for communicating architectural information as it provides an interactive display of 3D scenes. The paper discusses the handling of this software and the creation of self-running applications. It also offers a comparison with other applications with a similar 3D visualisation performance profile. The aim is to test suitability of the software packages for establishing 3D walkthrough models of sacred buildings, based on existing 3D models of destroyed Viennese synagogues. The paper explores and explains the conditions for data conversion and any follow-up uses. While certain restrictions exist, potential benefits for the virtual reconstruction context can be identified.*

KEYWORDS: *Virtual reconstruction; destroyed synagogue; Virtual Building Explorer (VBE); real-time walkthrough; perception.*

1. Introduction

What are the modern-day options of "re-creating" a building structure which no longer exists as a result of purposeful destruction? For more than 10 years, academic research has been undertaken into the virtual reconstruction of synagogue buildings in Vienna. Research must probably start with the question as to what type of information about the building has survived (planning and design documents, photographs, descriptions, etc.). Subsequently, a three-dimensional model will be produced. In the process, contradictory information needs to be checked for plausibility and/or information gaps filled in a plausible manner. A decision needs to be made about whether it is sufficient to present the respective building structure without its urban context or whether the immediate surroundings should be presented in a simplified manner (Martens and Peter, 2009). Another important issue is the level of detail used in the modelling.

The modelling process and the concomitant interpretation of available information have been comprehensively published (Martens and Peter, 2002 / 2010). This paper is concerned with possibilities of interactive viewing of an existing 3D virtual reconstruction, by using a self-running application instead of the original modelling software (ArchiCAD).

A particularly interesting form of visualisation of virtual building models became possible in 2005, when a Swedish software company (Zermatt VR Software) licensed its "game-engine" to Graphisoft, who implemented the *Virtual Building Explorer* (VBE) as a communications module in ArchiCAD in order to allow planners improved visual control of their building concepts and to offer the developers of the future structures a virtual walkthrough. With self-running VBE-based applications, users can easily navigate through a building by means of the mouse. "Global Illumination" gives the models realistic ambient lighting. Together with still-renderings and digitally created scale models, the VBE is one further way of utilising an existing three-dimensional CAD-model.

Section 2 explains how the VBE applications are created and what the connected requirements are, and section 3 takes a closer look at the performance range of the VBE from the user's perspective. The respective advantages and disadvantages of related software packages are assessed in section 4, and the section 5 presents the conclusions.

2. Requirements for the Creation of a VBE Application

Which requirements need to be fulfilled in the preceding 3D modelling process to facilitate the creation of a self-running *Virtual-Building-Explorer* application? An important factor is the size of the initial model. The higher the number of polygons, the larger the storage capacity and performance requirements for the computer running the VBE application. The 3D data are imported directly from ArchiCAD through an integratable add-on and saved as a VBE data model. The model is then opened in the actual VBE authoring environment (Fig. 1) for fine-tuning of the display quality (global illumination, shadows, transparency, etc.). This is when the actual compilation takes place in this software environment. It must be noted that "global illumination" may well take a few hours in case of a large model. For the final saving as a self-running application the user can choose between the Macintosh and Windows OS or save the model for both operating systems if required.

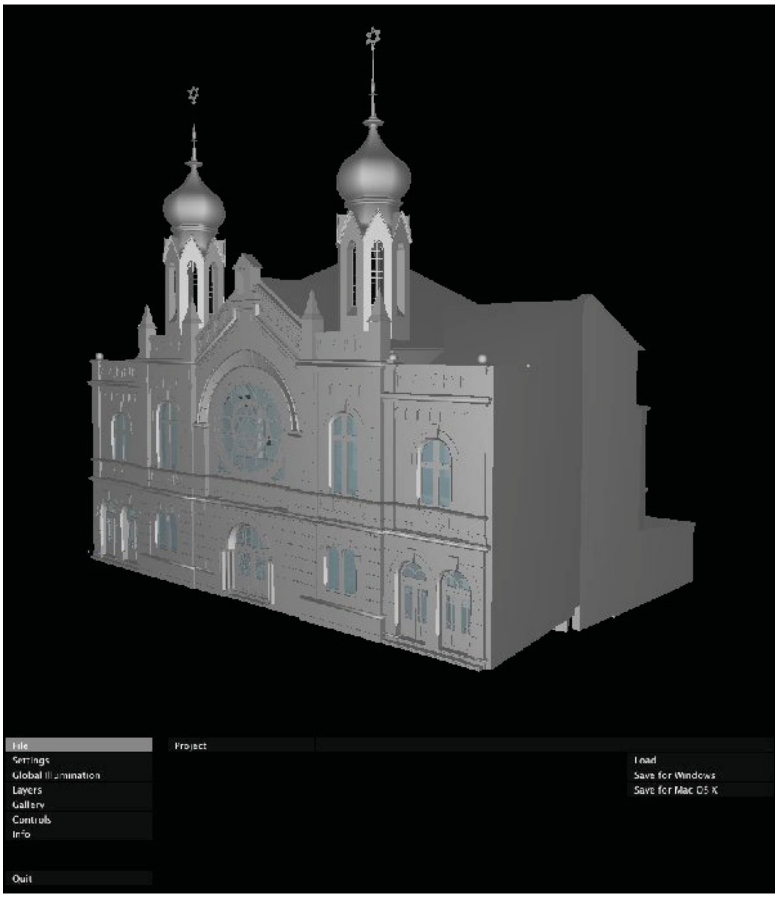

Fig. 1: 3D model of the synagogue at Kluckygasse (Vienna) during editing in the VBE authoring window.

It must be assumed that models of average complexity – i.e. in the 20-80 MB range – will not create serious problems. During modelling, the degree of abstraction (level of detail) needs to be given some thought. The exact adjustment of the VBE quality requires a high level of experience. Computation time will depend mainly on the use of global illumination, since the light model is calculated for each individual case.

The artefacts of which the 3D model is composed are usually placed on a kind of "greenfield", and the creation of a surrounding environment – albeit at a high level of abstraction – is recommended (Fig. 2). During the VBE application generation a virtual baseplate is created automatically. Crossing over the "edge" may lead to the user "falling" into empty space, and he will not be able to get back to the building in "walking mode". In order to prevent that from happening, it is advisable to provide for a structural boundary.

Normally, users will move through spaces devoid of people. Any desired humanoid figures would have to be modelled separately. They would be immobile. This can be compared to viewing physical models, where human figures are often placed inside the model.

The use of "realistic" surface patterns – so-called textures or shaders – can enhance the quality of the virtual model (they may also impair it, if they produce the impression of a multiplied pattern, or "tile effect"). The multiplication of a surface texture unit aims at giving the surface the appearance of a homogenous material. The edges of the pasted images need to be designed for seamless replication. Most software applications offer the choice of mirroring or sequentially arranging patterns. Usually, a texture does not consist of a single image of the desired material, but of at least three images which are superimposed on the surface to create the desired colour, reflectivity and bump. Creating a realistic materiality in terms of colour effect, light reflectivity (reflection, mirroring, gloss, etc.) is a real challenge. Navigation should be fast and stutter-free (= computing power), and the impression of the space should be as realistic as possible. Not unlike the developments with digital data formats in music and photography, we are ready to accept certain quality deficits in exchange for compact file sizes or other advantages.

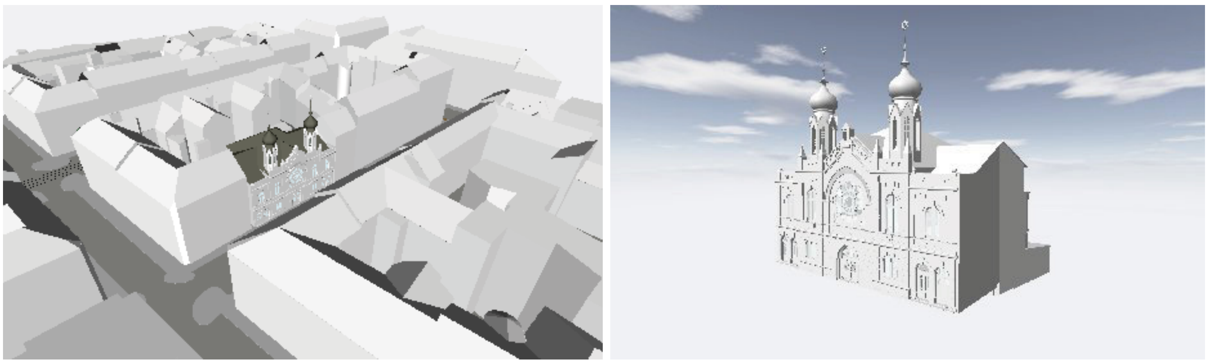

Fig. 2a-b: model representation with (ArchiCAD model) and without urban context (VBE application).

3. VBE from the End User's Perspective

Der *Virtual Building Explorer* is a self-running software application for the interactive communication of 3D objects and situations. This means that no additional software needs to be installed; a simple double click will start the presentation. Even an older computer will be able to cope with the software and the required starting time seems appropriate. It is, of course, interesting to know to which extent the software is self-explanatory. This question was studied with the help of eight master students who work on themes relating to virtual reconstruction. They were sent a demo VBE application of a sacred building and asked to explore it on their own and subsequently report on this experience in writing. The idea was to encourage free exploring, and "stumbling" was not considered a failure. We were also interested in the students' feedback on using this tool for the presentation of a (no longer existing) sacred structure. The following explanation is not meant to be a mere "how to" guide, but also intends to convey the practical experiences made with the tool.

3.1 Getting started and navigation

It takes only a short orientation phase to master the controls which are easy to use and intuitive. It is worthwhile, however, reading the information about the escape menu provided on the start-up window, as it facilitates getting help later on if needed. Users who would like to get the full flavour of navigation functions will have to use that menu, because it provides for a range of navigation options – from fly-mode to crouching-mode just about anything is possible. As an occasional user one will frequently consult the key shortcut menu.

The handling brings back memories of game-engine environments, since the letters W-S-A-D or the arrow keys are used for navigating. If the user feels unsure about that, the escape key will call up a menu with explanations at the bottom of the screen which shows all navigating options. Beginners will move very cautiously at first, but as nothing can be destroyed the initial inhibitions will soon be forgotten.

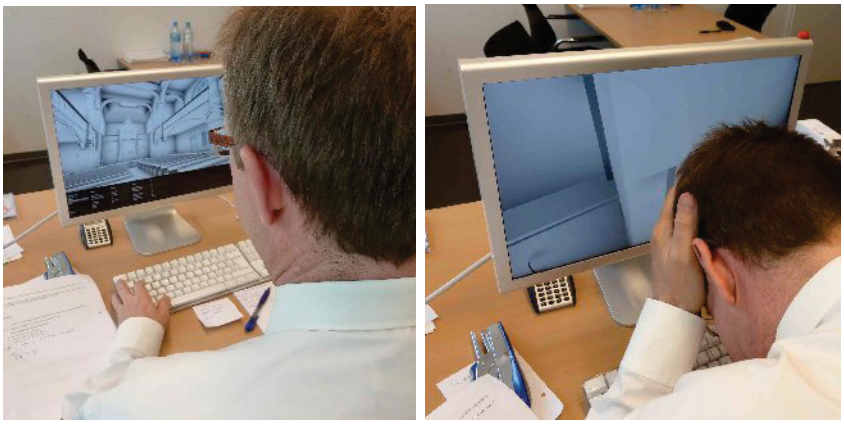

Fig. 3a-b: Using the Virtual Building Explorer (VBE) at the desktop computer: Just view it! Disorientation in virtual space can be a challenge and sometimes gives users a headache.

The most common modes of locomotion through the virtual model will be "walk-through" and "fly-through". Spatial boundaries and objects (walls, furniture etc.) stop the user in walk-through mode and the "collision protection" function means that the user is forced to a halt. Therefore, doors must be built into walled-in spaces. Only if parts from the ArchiCAD door library are used in the 3D model, will the VBE tool interpret them as "doors". The VBE will not, however, allow the user to pass through any door-like elements created with the help of other modelling tools. Stairs are correctly identified, and the viewer can walk up or down the stairs.

In fly-mode, the entire space is available for navigation and the user can move through obstacles such as walls like a ghost. A novice will probably sooner or later find him- or herself flying into nirvana and have to restart the VBE application to get back to the structure (Fig. 3a-b). Another "tragicomic" situation may arise if users (in walk through mode) are not perfectly familiar with the virtual structure and mistakenly leave the building, reach the edge of the baseplate and "fall off the edge of the world". This can be prevented by erecting a wall or fence around the site.

What is a "classical tour" (Fig. 4) through a Jewish sacred building like? Viewers will first get to the central aisle (ground floor), facing the *bimah* (also called *almemor*) and the Torah shrine behind it as they progress. Depending on the religious principles, the bimah – i.e. the rostrum where the Torah is read during liturgy – will be freestanding or very close to the Torah ark behind it. The structure and dimensions of the main room require the viewer to move his or her head to get enough information about the space. Walking straight ahead will soon have to stop and viewers need to consider how they want to continue the tour. Probably they will want to turn around and perhaps sit down for a short while. Or they may become interested in the side parts of the structure and sit down again. Depending on what they are interested in they may also want to visit the gallery or the winter praying room, if the synagogue has one. This will conclude the tour in every sense of the word. There will also be areas that are not publicly accessible and that fact should also be reflected in the virtual model, since the fly-mode gives the user virtual omnipresence and the possibility to satisfy any voyeuristic navigation wishes without restriction.

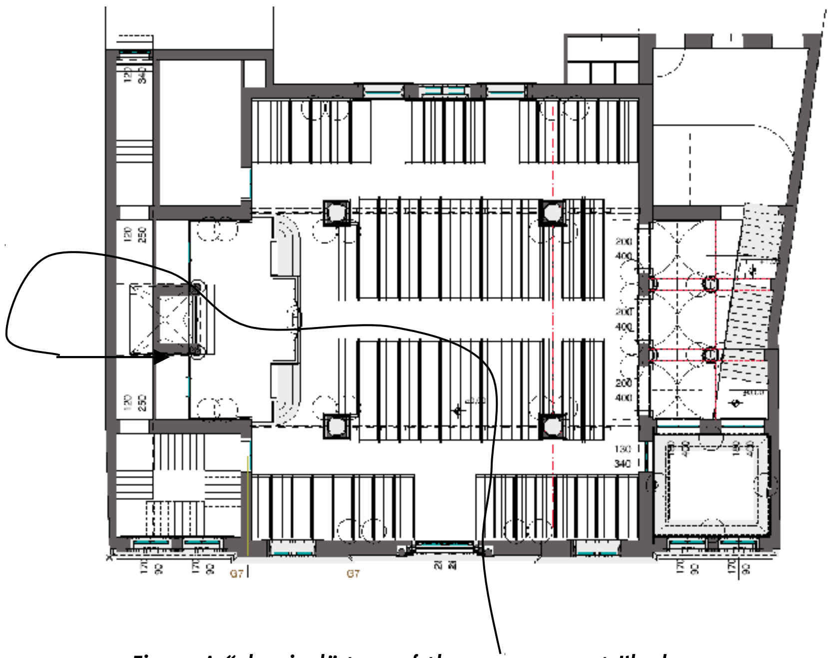

Fig. 4: A "classical" tour of the synagogue at Kluckygasse.

3.1.1 Mapmode: superimposed floor plan

For better orientation, the 3D presentation can be overlaid by a line drawing of the floor plan (Fig. 5). This feature is also known from computer gaming and provides simultaneous navigation and orientation without having to abandon the main scene. The arrow indicates the current direction of view. In shooting games, this type of orientation map is indispensable for "looking around corners". Mapmode facilitates anticipation of what lies ahead in large and ramified structures. Full-screen superimposition soon becomes irritating, however, and unfortunately there is no way of reducing the map size. There is also an unfortunate association with shooting games which seems very unsuitable in the context of a religious building.

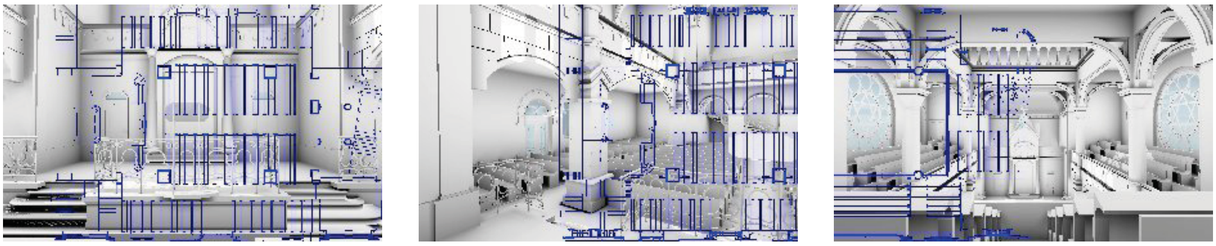

Fig. 5: Superimposition of 3D view and the floor plan showing the user's current position.

3.1.2 Unrestricted movement for the viewer

The movement through the structure is a kind of "digital endoscopic exploration". The speed cannot be adjusted precisely to that of a pedestrian, cyclist or car driver, since the mouse controls the viewer's movement: forward and back, also in combination with moving to the side. Up or down are also available options. The eye level and the viewing angle can be accurately pre-set by keyboard entry. The use of other user interfaces – e.g. WiiView remote controller etc., could also be considered (Fritz, et al 2009).

Some viewers have the impression of looking into a virtual world through special (blinkered) glasses. Usually the perspective is at eye level of a walking person. In fly-mode the viewer will of course lose touch with the ground. In other words, the overview perspective provided by fly-mode is useful but not particularly realistic. The control options, which are accessible through drag and drop or the right-click context menu are convenient. The software also permits one-hand (real-time) navigation by means of the keyboard (acceleration/deceleration of the navigation speed, etc.). In combination with mouse control of the direction of view, the tool creates a realistic impression of movement through the structure. Intuitive handling is not possible in any situation, though. When the escape menu is open, movement with the arrow keys is still possible, but mouse control of the direction of view is disabled. Users who are not aware of this will be puzzled why they are no longer able to "pan the camera" with the mouse.

File	Menu	Escape	Fly Mode	F
Settings				
Global Illumination	Movement	W S A D	Info Tool	I
Layers	Move Fast	Shift	Measure Tool	M
Gallery	Move Slow	Control	Outlines	O
Controls				
Info	Crouch	Alt	Sun Shadows	F3
	Jump	Spacebar	Screenshot	F5
	Lift	Y	Parallel View	F8
Quit	Lower	H	Map Mode	Backspace

Fig. 6: The options under the Controls menu.

3.1.3 Layers as information structuring tools

The layer structure enables a better understanding of the view and the structural elements it contains. Hiding individual layers serves to highlight particular elements. This option has to be taken into account when creating the model to enable the targeted hiding and showing of layers in the VBE. As the layer names are taken over from ArchiCAD, choosing clear names for the individual layers is recommended. When layer composition is appropriately planned, the layering will also allow for presenting different epochs (with different building states).

Fig. 7: Example of a layer structure (synagogue at Kluckygasse).

3.1.4 The VBE Gallery to assist exploration

The option to save animations is useful. The "autoplay" function may be used for info stalls and similar presentations: whenever there is no visitor present who actively moves through the digital model, the software will run a predefined animated sequence. A passive viewer will thus get an impression of the model without having to worry about navigation.

As there is a gallery, an integration of defined camera positions (reference points and viewpoints) would be desirable. This would not have to be restricted to predefined relevant viewpoints, but, in case of a large and complex model, should also include individual positions in different spaces or on different levels. In this manner, the viewer would not constantly be forced to move towards the starting position (= the camera position defined in ArchiCAD).

Fig. 8: Within the VBE gallery, pre-defined viewpoints can be retrieved.

3.1.5 Settings: less may be more

Settings include a large number of options. It might be advisable to restrict options radically for certain types of users and only enlarge the range when required. Are there many viewers who would like to start the session with dealing with render modes, changing backgrounds and adjusting transparency? A suggestion for the info tool (Fig. 9) would be to include descriptions of elements, e.g. what a *bimah* is or what the significance of the "Holy Ark" is (vgl. Pauwels, et al, 2010). The measuring tool is easy to use and provides dimensions of elements in the model. It is more difficult, however, to get exact measurements, since the snap points of structural elements such as ceilings, walls or roofs defined in the ArchiCAD software environment are not exported to the VBE application.

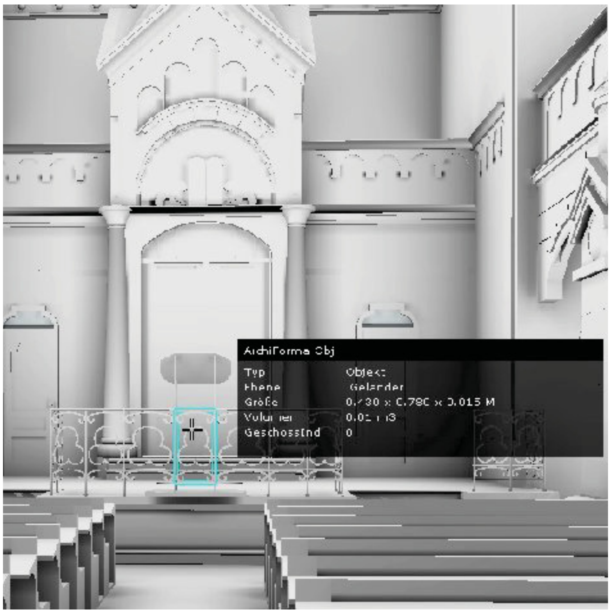

Fig. 9: Additional information about model elements can be displayed.

Unfortunately, changed settings cannot be saved, which means that they have to be repeated with every new start of the VBE tool. Another impractical point is the fact that it seems impossible to switch to another software while the VBE is running, e.g. in order to write a text. It would be helpful to be able to minimise the VBE or switch to the desktop.

After having looked at the creation of a VBE application and providing an overview of the way the *Virtual Building Explorer* (VBE) works, the next section will compare it with other software environments.

4. Alternative Software Environments

What are possible alternatives to the *Virtual Building Explorer*? This section explores other applications, without claiming to be exhaustive, which provide a stand-alone mode of display of 3D models. The claim to be independent of software may seem paradox at first. What we mean by that is that no proprietary software is required for viewing the model. A paragon example would be the *universal PDF format*, which was introduced in 1993 and enables document viewing across multiple platforms.

With the development of *3D-PDF,* Adobe provides a way to display 3D designs, also including embedded animation sequences. The main area of use, however, seems to be the engineering sector with technical publications (assembly plans) for engineering products. Architectural designs are a niche market, including e.g. the documentation of building components. The creation of a 3D-PDF document is relatively time-consuming and can only be done under Windows (while the finished file can also be displayed under Mac OS). A selected perspectival view of the model is linked to the .U3D file (previously saved from the ArchiCAD model. The user interface is easy to understand and offers various display and lighting options. The 3D model can be explored in walk-through or fly-mode. On the downside, loading and navigation speed (depending on model size) seem particularly slow.

QuicktimeVR has also been around for many years. Since 1994, it has been enabling users to "walk into" virtual spaces. It is a useful tool for giving a viewer the impression of being "inside" a virtual structure. The software uses 360° panorama images for navigation and the creator controls which part of the space is shown. The computation time for a panorama image has been reduced by several factors owing to modern computer processing power and does not represent a major problem for a mid-range computer. On the downside, the linking of individual viewpoint (by means of an authoring tool) is time-consuming. As soon as several panoramas have been linked through hot spots, the user moves from point to point by mouse-click.

Google SketchUp also offers navigation through a model. Again, there is a choice of walk-through or fly-mode. The direction of movement can be controlled with the arrow keys and by holding down additional keys. Unfortunately, walkthroughs start to stutter soon, even with smaller data models. The use of larger and more detailed imported models is not really advisable for the time being. An attractive option is viewing the model in a *GoogleEarth* environment (including annotations!), although the viewer can only navigate outside of the structure and has no possibility of entering a building. SketchUp models can also be used in game engines by means of a plug-in function (Lowe, 2009).

Blender Game Engine is an open source application used for modelling and visualisation (animation). The package includes an integrated, programmable game engine, which can be used from within the programme or on a player tool which comes with the software. The setup of the engine is not self-explanatory but can be quickly learned with the help of user-tutorials which are available on the internet free of cost. For the present case, two data formats (.3DS, Wavefront-.OBJ) were tested as interfaces between ArchiCAD and Blender. The Blender model can be explored in walk-through or fly-mode. Fly-mode is controlled by moving the mouse left or right, up or down. The speed of moving forward or backward is controlled by turning the scroll wheel in the desired direction. The more the wheel is scrolled, the more quickly will the camera move through the virtual space. In both modes, Blender supports shading and texture mapping, but not illumination. In practice, it has been found that a 10 MB (ArchiCAD) model of a synagogue will grow to approx. 100 MB in the export file and end up as a 60MB file in Blender. Hence, a high performance CPU and appropriate RAM size are required for smooth navigation.

5. Conclusions and Outlook

This paper studies the possibilities for making a 3D CAD design available to a wide range of viewers with the help of special software viewing tools. The designs used in this context are virtual reconstruction models of destroyed synagogue buildings. It must be stated that this exploration does not aim at physical reconstruction of the building stock, as almost all of the former sites are occupied with other structures or functions, and there would not be sufficient demand on the part of potential users. The Virtual Building Explorer (VBE) can be used to generate self-running applications from ArchiCAD models and make those models available in a slimmed down format.

The VBE tool, which is discussed in detail, has many features known from game engines. The fact that users may be reminded of shooter or horror games while looking at reconstructed sacred structures may be an issue of concern. It needs to be studied whether this would make the tool more or less appropriate for the public at large. Further consideration should be given to the target user group for such applications. Architects, archaeologists or (art) historians would perhaps be able to distance themselves from such associations. If the target user group includes wide sections of the population, certain restrictions in the viewing format might be considered, particularly in the case of models of sacred buildings. On the upside, the software tool does not require a long training period. Another question worth exploring is whether the virtual environment might give rise to boredom after spending some time there.

Since the (virtual) reconstruction of synagogue buildings is underway in many European countries, an exchange of virtual environments would be useful. The idea of creating a repository of self-running applications seems particularly appealing.

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http://www.graphisoft.com/products/virtual-building-explorer/

http://www.adobe.com/manufacturing/3dpdfsamples/3dsolutions/

http://www.apple.com/quicktime/technologies/qtvr/

http://sketchup.google.com

http://www.blender.org

BUILDING INFORMATION MODELING (BIM) PREREQUISITES IN IRAN AS A DEVELOPING COUNTRY

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ABSTRACT: *By improving the usage of Building Information Modeling (BIM) and high technology methods and systems in AEC industry as a way to have a more efficient industry in developed countries, developing countries has started to move toward these aims, more efficient, collaborative industry.*
The difficulty on using these systems and all other ones are that they need their defined infrastructures and only in that way all the promised positive aspects of these systems can be achieved. It is obvious that in developing countries by being pioneer in founding and implementing these new systems these needed infrastructures and preparations are take into consideration more and more while in developing countries because of the time-technology gap and obvious cultural behavior differences those infrastructures have a different meanings.
In this paper at first we had a historical overview on BIM, its backgrounds and its promises as positive impact of using it to the industry and the surveys on the factors that help BIM to be more effective systems.
Secondly we consider the ability of BIM application in design phase and those needed infrastructures in Iran as a sample of developing countries.
Hope this article makes a contribution to finding a better solution in implementing the best systems in developing world.

KEYWORDS: *Building Information Modeling, BIM Prerequisites, historical view, Virtual Reality, survey, Developing Countries*

1. Preface

Building Information Modeling made an unprecedented revolution in the construction industry. This technology employs digital modeling softwares for more effective AEC projects design, build and management and hence increases the productivity of active firms in AEC industry.

At the same time BIM collapse the old boundaries between different parts of the project and help them to share their knowledge throughout project lifecycle. And so it helps the professionals to have a better understanding of the project by integrating the knowledge and experiences of all the involved members of the project.

This will lead to more productivity, more accurate scheduling and budgeting and better and more sophisticated life-cycle management. (Kymmell2008)

2. Historical view:

Application of different types of simulations through history has been recorded. During renaissance the architects made wooden models of the project; these are samples of project simulation. And similarly diagrams, drawings, details which have been used for hundreds of years as build guides, although the information on these sources were many minor and the data were not fully integrated.

With the advent and application of personal computers, they help designers involved in construction projects for decades. But this contribution was in the field of drawing and drafting most of the time and although it helps designers to be more accurate but it has deficiencies.

In 1974 Eastman along with five others wrote an article about the problems related to communication tools in construction process. These tools included drawings and details. Part of the issues that Eastman and colleagues have referred to was the following:

- 2D drawing basically imposed waste matters to design process, since that for describing a 3D space by means of 2D drawings it requires at least three drawings; and it means that some of the faces repeat in two of these drawings. Repeated faces in different drawings with different scale and view with no integrated connection to each other means that by changing one face in one drawing one must check and change that face in every other drawings.
- Common 2D system requires spending large amount of energy to keep all drawings and details up-to- date. But despite spending as much effort as possible, there is always the risk of not up-to-date information on drawings.
- Another key point in this issue is the relation between data in the drawings and the data needed for analysis. As most of the data in the drawings are graphic information and not usable for analysis softwares, these data must manually re-entered in these softwares.

Their solution to respond to these issues were using a computer system that can store all the design related information and make necessary changes in it automatically, and make using of these information for construction different analysis possible. They call this system *Building description System (BDS).* (Eastman-1974)

The issues which Eastman expressed in his paper more than 35 years ago were still considered as fundamental issues facing AEC industry, however by time passing by the size of the problem reduced but still the presence of them in construction project lifetime cycle is obvious.

In last few decades, architects and engineers start to make models of their projects in 3D instead of 2D environment, but in most cases these cases complete substitute of 2D drawings for communication and permits were not achieved, but this was the start of new approach to complete simulation of project in virtual environment.

Simulation refers to an integrated process for design and construction of a project in virtual environment. This process uses the benefits of software packages and is located in the computer environment.

3. The concept of BIM:

Building information Modeling (BIM) is a wide concept which different groups and associations look at it from different point of views, define it and make their efforts to help it developing. For this reason comprehensive understanding of it is not accessible by means of one definition.

But generally speaking BIM is virtual simulating of the project by means of parametric, information rich 3D models of construction parts. Information in a BIM can be used during project lifecycle period.

There are different terms in various sources which are related to BIM concept, including items noted below:

Table 1: Broad terms based on BIM concept: (Bilal Succar,2009)

Institute/Investigator	**Term/Phrase**
Fully Integrated & Automated Technology	Asset Lifecycle Information System
Autodesk, Bentley Systems and others	Building Information **Modeling**
C. Eastman	Building Product Models
International Alliance for Interoperability	Building SMART™
International Council for Research and Innovation in Building and Construction (CIB)	Integrated Design Systems
American Institute of Architects	Integrated Project Delivery
University of Salford – School of the Built Environment	nD **Modeling**
Graphisoft	Virtual Building™
Stanford University – Centre for Integrated Facility Engineering	Virtual Design and Construction & 4D Product Models

3.1 BIM original ideas:

The most useful aspects of BIM are closely related to three main ideas:

- Parametric Design
- Object oriented design
- Model intelligence

Table 2: differences between CAD and BIM are discussed.

BIM	**2-D CAD**
Describing the subject with a single integrated 3D model in virtual environment. All plans and views can be extracted from this model.	Describing the subject with different 2D plans and views (like: plan, view, section …)
Various parts of the model are related to each other and changing in one of them will lead to proper changes to other related parts.	Views, plans and other drawings are not related to each other and by change in one of them other changes must run manually.
All the model parts and their relationship and changes are checked by model intelligence.	According to lack of intelligent connection of different drawings all the changes is done by personnel.
Parts are full of information and contain real, accurate construction and other needed information	Most of the data is graphic information. For example in a 2D cad drawing a wall is a set of lines and does not have real meaning and information.

4. The scope of BIM application in Iran:

Iran is located at the heart of Middle East, has vast connections with developed and developing countries and has always been one of the leading countries in research and industrial activities among developing countries. Therefore, according to cultural close proximity to other countries, studying scope and prerequisites to implement a system in Iran could help better understanding of developing countries context to use new system of communication and integration in AEC industry.

In a survey which was conducted among consulting companies in Iran during 2010-2011, the problems and issues related to 2D drafting was clearly seen and this study also shows the eagerness of participates in new ideas of BIM, but still a very small percentage of the participants know about this system. (Abtahi 2011)

As BIM is a new system and with its great potentials, for maximum efficiency and reducing the undesirable effects in countries which haven't started using this system or at the first steps need to provide required infrastructures.

5. The impacting factors on BIM

In an overall look to BIM productivity and efficiency, three main factors can be presented.

- BIM stakeholders
- Cultural context
- Industrial context

Below, these factors discussed briefly and after that BIM application prerequisites are mentioned.

5.1 BIM stakeholders

Considering new technology and its concepts the groups below are provided as the main stakeholders of BIM application.

- Users: architects, engineers, contractors, employers and other involved personnel in construction process.
- Legislators and control authorities
- Suppliers: software suppliers- product suppliers
- Academic and research institutes: universities, research institutions and …
- …

Each system and technology need complete coordination of all these stakeholders together for maximum productivity and efficiency.

5.2 Cultural situation

Another impacting factor on a new system application is considering the cultural characteristics of the society. For example a stronger connection to traditions and more closed way of thinking is of general characteristics of developing countries, so in the process of implementing new systems with different concepts and notions this context and characteristics must be considered.

Industry situation:

Noticing the AEC situation and characteristics is so important to decide about the best system helping the current industry to be more efficient, and so this is one of another factors in implementing level of new technology in a country.

6. BIM application prerequisites:

Due to factors discussed above and BIM characteristics, below the required infrastructures for implementing BIM is discussed.

(as each title needs about a page of description, here I only mention the titles and these items will be explained further in the conference .)

6.1 Change:

The main concept and base of BIM is Change. Change in ideas, tools, strategies, perspectives and objectives. All of these mean a basic change in the way of thinking and cooperating with other people and change in all the bases that define our activities as human spices. These changes require the change in issues below:

6.1.1 Fundamental changes:

The first part and the most important aspect of change for using BIM is the change of beliefs, thoughts and inner attitudes. This is one of the most important factors to implement BIM. This issue is important because BIM is not a pack of softwares or tools but it is a complete *system* of attitudes, objectives and tools. And implementing it without necessary thought and belief system is incomplete and would not lead to integrated efficient new system. Some of these fundamental changes are items below:

- Broader perception of the project and its lifecycle period.
- Broader understanding of the project stakeholder concept

6.1.2 Internal changes

- The desire to change the tools
- The desire to change the way of working
- Integration
- More responsibility
- More team work
- The desire to share information

6.2 Education and research:

As BIM is a new system and involved personnel in construction process are not familiar with its concepts, potentials, goals, risks and other aspects of this system to achieve the most potential aspects of BIM in AEC industry a vast and integrated education structure is needed. Without learning it is not possible to achieve a better more cooperative, efficient industry.

Different levels of education are required in AEC industry:

6.2.1 Academic education and researches:

- Coordinating the education methods with the new system
- Introducing new systems of education

- Researches on new issues and developing aspects
- Education and researches on defining and developing the integrated national BIM standard
- Introducing the new system to the industry and companies.

6.2.2 Personal trainings:

- Learning and understanding new concepts and attitudes
- Learning to work with new softwares

6.3 Define and providing of supporting structures :

- Setting new rules and obligations
- Providing required hardwares and softwares
- Forcing suppliers to follow new rules
- New rules to use new system as the base of the AEC works.

6.4 Suppliers related issues:

Without intelligent and information rich models by suppliers which used by BIM softwares to build the project and used for different analysis purposes, it is not possible to achieve a BIM. So suppliers and manufacturers of products used in AEC industry have an important role in implementing new system, and of course this changing need the cooperation of education, regulations and all the involved parts.

7. Conclusion

The BIM is a new and promising approach in Iran which is gradually gaining acceptance by the owners, architects, engineers, and contractors, but for achieving complete potential of this new system it needs its fundamental prerequisites. These factor and items are not just physical items but in addition to them the traditional society of Iran must change and acquire thinking and objectives of this system, which are fundamentals of a more cooperative, integrated approach to AEC industry.

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DESIGN AND IMPLEMENTATION OF AN INTERACTIVE GUI FOR BIM SYSTEMS

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ABSTRACT: *The construction industry is moving towards the application of Building Information Modeling (BIM) for managing and integrating engineering information efficiently. Today, engineering consultant companies, construction companies and architectural companies invest much research into the development of BIM to integrate and visualize engineering information for higher productivity. Currently, BIM desktop applications such as Autodesk Revit, Bentley Architecture, Tekla Structures and Gehry Digital Project, can only integrate and manage information on-site. This therefore makes it difficult for various project participants at other sites to efficiently obtain and update information. Furthermore, the user interfaces of these systems have been designed based on the designers' preferences, rather than being oriented towards the needs of general users. The abovementioned conditions therefore restrict effective and efficient communication and distribution of information amongst different BIM users located at disparate sites. To address these issues, this research designed and implemented an interactive Graphical User Interface (GUI) to improve visualization and manipulation in BIM systems to help general users to acquire required information efficiently. In this research, we propose a set of new UI design principles for BIM systems based on contemporary GUI design rules and principles. This paper also describes the design and implementation of an effective UI using the Microsoft .Net environment and Silverlight for Rich Internet Application (RIA) for access to, and visualization of, information through Web applications. An innovative element of this research is the utilization of multi-touch technology to increase the richness of human-computer interaction. This interactive GUI facilitates information exchange between various project participants, such as construction site personnel, project owner and construction management company, for effective and efficient project management.*

KEYWORDS: *Building Information Modeling, Data Visualization, Multi-Touch, Interactive User Interface*

1. Introduction

During the life cycle of an engineering project, voluminous amounts of data and information are usually created. The construction project team must consider a wide range of information when controlling the project and making project decisions. Building Information Modeling (BIM) is a relatively new technology that facilitates better information integration and management. Many engineering companies employ BIM for information integration, visualization and parametric design, to reduce both the duplication of work and the complexity of interface integration to save time and money. BIM was coined in early 2002 by industry analyst Jerry Laiserin to describe virtual design, construction, and facilities management. BIM processes revolve around the generation and use of virtual models that make it possible to share information on a common platform throughout the entire building industry [Eastman et al., 2008]. Currently, most BIM systems are independent and stand-alone, making it difficult for project participants not physically at the system to efficiently operate the system and access data. Furthermore, the user interfaces have usually been designed based on the designers' preferences and have not been geared towards more general usage. These conditions currently restrict effective information communication and distribution amongst BIM users located at different sites. In our previous work, we utilized the concept of Software as a Service (SaaS) and Cloud Computing and developed a visual system, called "Cloud-BIM system", for BIM visualization and manipulation to overcome time and distance limitations [Chuang, 2011]. This research aimed to redesign and implement an interactive Graphical User Interface (GUI) to improve visualization and manipulation in a Cloud-BIM system to enable users to acquire the required information efficiently. Several known GUI design issues have been considered. Firstly, the GUI must be easy to use; recently there has been renewal of interest in how to design effective UIs for applications. For example, Shneiderman et al. proposed eight golden rules of UI design [Shneiderman et al., 2009]; Jenifer Tidwell captured UI best practices and reusable ideas as design patterns for facilitating UI design [Tidwell, 2010]; Fowler et al. wrote a guidebook on good UI design for web applications [Fowler and Stanwick, 2004]. In this research, we referred to the design principles developed in the above-mentioned literature, and also considered common practical uses of engineering applications in the development of our GUI design principles for engineering systems. A key second issue is efficient GUI interaction. When exploring the aspect of interaction, four major components have to be addressed [Sharp et al., 2007]: (1) The end user; (2) The person who has to perform a particular task; (3) The context in which the interaction takes place; (4) The technological systems that are being used. Each of these components has its own qualities and should be considered in the interaction between the computer system and the user. Consequently, this research has utilized multi-touch technology to increase the level of human-computer interaction to facilitate better usage of BIM systems. Thirdly, the user should be able to manipulate the GUI without time and distance limitations. Therefore, this research focused on the design and implementation of a web-based GUI. Layout is another important issue for GUI design. Some new techniques have been recently proposed for facilitating the ease of GUI layouts. For example, Feiner (1988) used the grid concept for facilitating automatic layout of GUI; Vanderdonckt et al. (1994) summarized the range of visual techniques that could be exported from the area of visual design and further exploited for UI design. These visual techniques provide the designer with a wide range of means for laying out Interaction Objects (IO). To address the above-mentioned issues, this research implemented an interactive GUI based on a Cloud-BIM system, which can facilitate anytime and anywhere communication and information exchange between project participants, and also enable project managers to access required information to managing their projects effectively and efficiently.

2. Human-Computer Interaction

The construction industry has become more dependent on computers and information technology (IT), with the increased generation of information in electronic forms, and increased visual content. With such increasing dependence on visual, electronic content, the design of environments for effective human-computer interaction to enable users to obtain relevant information from the systems they interact with has become more important. Dix et al. proposed that successful systems should be designed with the three "use" words - 'useful', 'usable' , and 'used', in mind so that the product is successful [Dix et al., 2003]. Human-computer interaction has been described in various ways [Benyon et al., 1998; Sharp et al., 2007], but the unifying concept is that of the technological system interacting with users in a seamless manner to meet users' needs [Lester, 2009]. Generally, the human-computer interactions of current BIM systems are designed for mouse and keyboard manipulation. With rapid technological developments, multi-touch technology with accompanying higher levels of interactivity has become popular. Multi-touch sensing enables a user to interact with a system with more than one finger at a time, as with chording and bi-manual operations. Such sensing devices are inherently also able to accommodate multiple users simultaneously, which is especially useful for larger interaction scenarios such as interactive walls and tabletops. As early as twenty years ago, Ben Shneiderman (1991) had already noted that touch screens have several advantages over other input devices:

- Touching a visual display of choices requires little thinking and is a form of direct manipulation that is easy to learn.
- Touch screens are the fastest pointing device.
- Touch screens have easier hand-eye coordination than mice or keyboards.
- No extra workspace is required as with other pointing devices.
- Touch screens are durable in public-access and in high-volume usage.

Presently, many researchers have invested much effort into the development of touch technology, believing that it increases the efficiency of Human-Computer Interaction (HCI) and brings much convenience in communication and information distribution. For example, Moscovich (2007) presented a number of novel interaction techniques that illustrate the benefits of multi-touch interaction. Over the past few years, multi-touch UIs have rapidly emerged from research prototypes into mass market products [Scholliers, 2010]. This evolution has mainly been driven by innovative devices such as Apple's iPhone or Microsoft's Surface tabletop computer. Interacting through gestures with fingers or hands requires new interaction concepts and UIs. In this context, this research has implemented an efficient GUI to extend the traditional GUI of BIM systems that supports traditional input devices, and also uses multi-touch panels at same time. Table 1 shows the main functions of input devices for HCI.

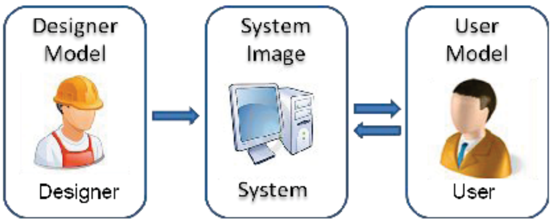
Table 1: Main functions of input devices

Device	Type	Main Function
Mouse 	• Mechanical • Optical and Laser • Inertial and gyroscopic • 3D • Tactile	• Select • Scroll • Drag and drop • Point
Keyboard 	• Membrane • Dome-switch • Scissor-switch • Capacitive • Mechanical-switch • Optical	• Key-in • Shortcut • Control software or game • Give commands to the operating system (e.g. Control-Alt-Delete)

Device	Type	Main Function
Multi-Touch Panel	• Resistive	• Write
	• Surface acoustic wave	• Select
	• Capacitive	• Move
	• Acoustic pulse recognition	• Scale down and Scale up
	• Dispersive signal technology	• Scroll
		• Rotate

3. Design Principles of User Interface

The UI is the most important component when users interact with any system. The more intuitive the UI, the easier it is to use. Moreover, the better your UI the more your users will like to use it, increasing their satisfaction with the work that you have done. Therefore, the design of any UI should be user-oriented. Norman (1986) explains that a user can manipulate a system easily if the "user model" is closely aligned with the "design model" as seen through the "system image", as shown in Figure 1. This project has proposed a set of design principles based on the above-mentioned concepts. Table 2 shows the key design principles for UIs utilized by this research. Shneiderman (1997) proposed eight golden rules, derived heuristically from experience and applicable in most interactive systems after proper refinement, extension and interpretation. These principles cover almost all aspects of UI design. Tidwell (2005) captured UI best practices and reusable ideas as design patterns for facilitating UI design. Nielsen and Loranger (2006) shared their insightful thoughts on web usability for webpage, content, site, and intranet design. Mayhew (2008) proposed a set of design goals along with the general characteristics that any good interface should have. ISO 9241-171 (2008) provides guidance on ergonomics and specifications for the design of accessible software for use at work, in the home, in education and in public places. From these principles, one general point becomes very clear: "Always keep users in mind". To design a successful interface, the human factor must be given first priority. Often, design principles have to be traded-off against other constraints or each other, and have to be refined or extended according to a particular context. In order to effectively apply these design principles, the users' tasks and requirements should be fully understood.



- **Designer Model:** the mental model of the system held by the designer.
- **User Model:** the mental model of the system held by the user.
- **System Image:** the physical structure which has been built including documentation and instructions.

Fig. 1: Mental model for UI design

Table 2: Design Principles of User Interface

Scholar	Design Principles of User Interface	
Ben Shneiderman (1997)	• Strive for consistency • Enable Frequent users to use shortcuts • Offer informative feedback • Design dialog to yield closure	• Offer simple error handling • Permit easy reversal of actions • Support internal locus of control • Reduce short-term memory load
Jakob Nielsen (2005)	• Visibility of system status • Match between system and the real world • User control and freedom • Consistency and standards • Error prevention	• Recognition rather than recall • Flexibility and efficiency of use • Aesthetic and minimalist design • Help users recognize, diagnose and recover from errors • Help and documentation
Jenifer Tidwell (2005)	• Safe exploration • Instant gratification • Satisfying • Changes in midstream • Deferred choices	• Incremental construction • Habituation • Spatial memory • Prospective memory • Streamlined repetition
Deborah J. Mayhew (2008)	• User compatibility • product compatibility • Task compatibility • Work flow compatibility • Consistency • Familiarity • Simplicity • Direct manipulation	• Control • WYSIWY • Flexibility • Responsiveness • Invisible technology • Robustness • Protection
International Organization for Standardization ISO 9241: 171 (2008)	• Suitability for the task • Self-descriptiveness • Controllability • Conformity with user expectations	• Error tolerance • Suitability for individualization • Suitability for learning

In this research, we have considered design and implementation of an interactive GUI under the following key aspects: (1) requirements of BIM systems; (2) multi-touch technology; (3) above-mentioned design principles of UI. We also propose seven design principles for GUIs for manipulating the BIM system through the internet and multi-touch panels.

- Button design should be simple and meaningful and located in obvious areas to assist users to learn how to use the system easily.
- System logo and project information should be located in top-left location for easy visual recognition.
- Accessing "Button" is a shortcut to assist user manipulate the system efficiently, so designers must create useful buttons according to the frequent functions of BIM system.
- Each page should provide a search toolbar for users to search for and obtain applicable data easily and quickly – the most important way users discover the integrated data model.
- Providing different view windows for different applications and user needs.
- Designing interfaces to have similar operations, and use similar elements for achieving similar tasks. This also enables people to quickly transfer prior knowledge to any new context and focus on relevant tasks.
- Providing significant and actual properties of an object to equip users with deeper understanding of the process or product.

4. An Interactive GUI Design and Implementation

4.1 System Framework

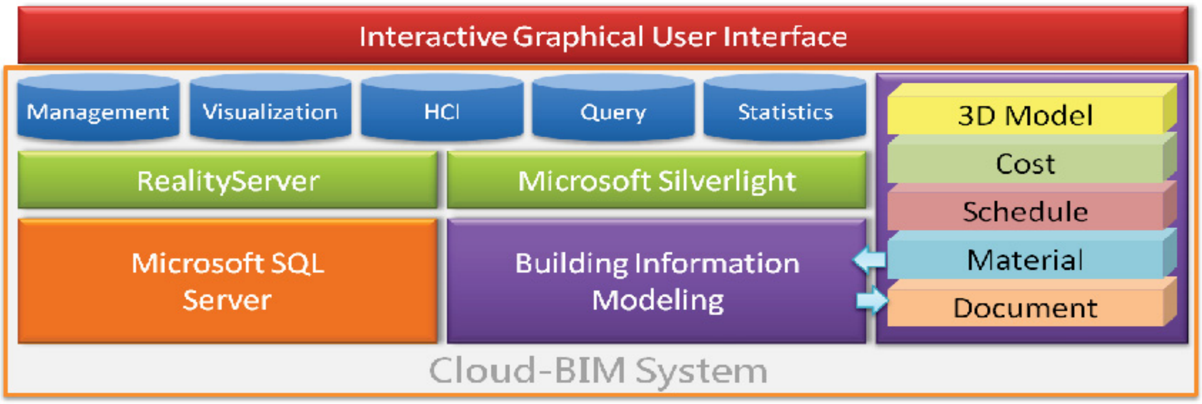


Fig. 2: System framework

This research designed and implemented an interactive GUI based on the Cloud-BIM system that we had recently developed. Figure 2 shows how the interactive GUI was implemented according to the design principles discussed earlier. We used Silverlight for Rich Internet Application (RIA) and RealityServer for 3D visualization in the Microsoft .Net environment, to enable users to access and visualize information through Web applications. The system comprises the integrated data layer which includes the BIM and Microsoft SQL Server for storing the entire set of information. The following five modules are also provided to assist users in project management:

- **Management:** This module is responsible for managing project information, and provides functions such as create object, update object, delete object and save object.
- **Visualization:** This module deals with object visualization in different forms, such like 1D text, 2D plan, 3D model and 4D simulation for facilitating users in acquiring the information they need.
- **HCI:** This module provides functions for users to manipulate the web-based system using a multi-touch panel. At this stage of research, only basic gestures such like locate, rotate, scale up, scale down, and move, have been implemented and supported.
- **Query:** User can input attributes to search for relevant files and then access the data for viewing or printing.
- **Statistics:** This module provides functions to calculate statistics pertaining to various aspects of the project to summarize and understand the current project status.

4.2 Main Toolbox

Figure 3 presents the layout of the main toolbox. The top-left location is the most familiar location for starting the use of any system. Therefore, the system name or logo would be easy to recognize when located there. Users can also conveniently commence searching for the data they need using the adjacent search toolbar. "General Functions" also enable the user to quickly access commonly-used functions such as open, save, help and print. In addition, the user can view the location of the construction site in Google Maps. At extreme right of the toolbox, User can click specific buttons – 2D, 3D and 4D, to switch between different GUIs of different views to browse for and obtain the information they need.

5. Demonstration

An engineering project was used as an example to test and demonstrate the new interactive GUI of the Cloud-BIM system. Figure 4 illustrates the 2D UI of our system. The user can select the drawing that is listed in Frame A and then view it in Frame C. In Frame B, the can click on the relevant button to switch the type of drawing list specified in Frame A. Figure 5 shows the UI of the 3D view. The window on the left provides the set of buttons for the user to select and view specific objects quickly, such as a column, beam or wall, along with data on the objects' properties. Frame C, is where the visualization of 3D models is provided. The 3D view also provides functions for the user to manipulate the 3D models, such as locate, rotate, scale up, scale down, and move.

Fig. 3: Main toolbox

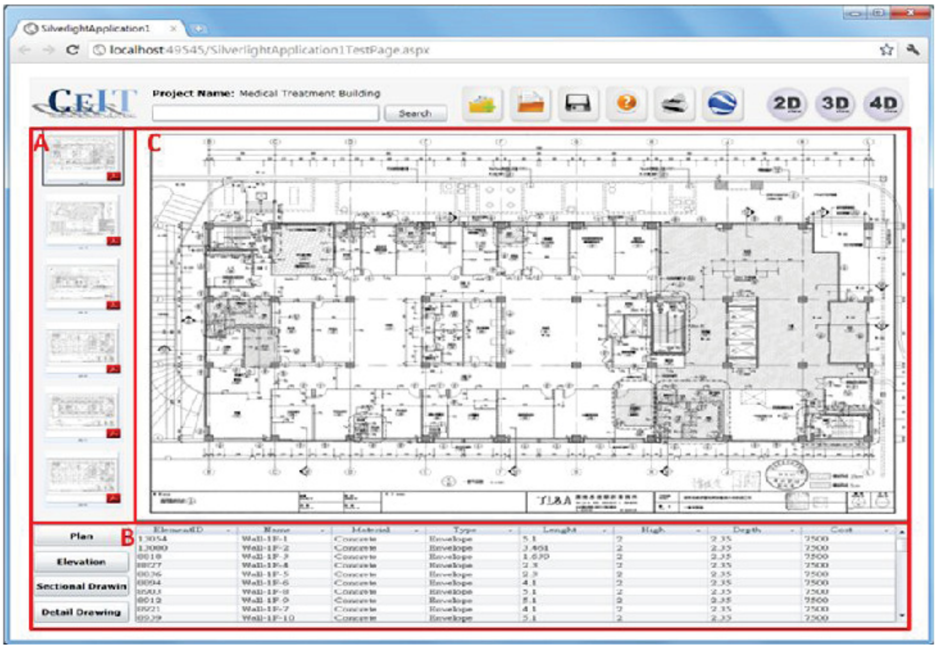


Fig. 4: The interactive GUI of 2D View

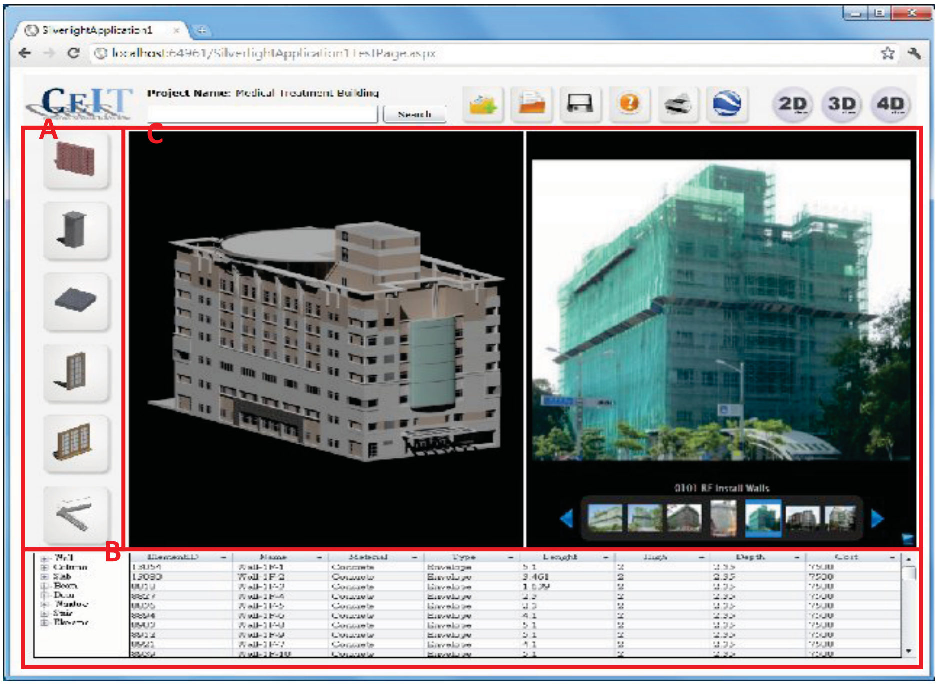


Fig. 5: The interactive GUI of 3D View

Figure 6 illustrates the UI of the 4D view. The user can select different simulation time periods, as indicated in Frame A. The bottom window is used to display related information for simulation scheduling as indicated in Frame B. The user controls the actions within the construction simulation, as indicated by Frame C. The 4D simulation will be displayed in the center window, indicated as Frame D.

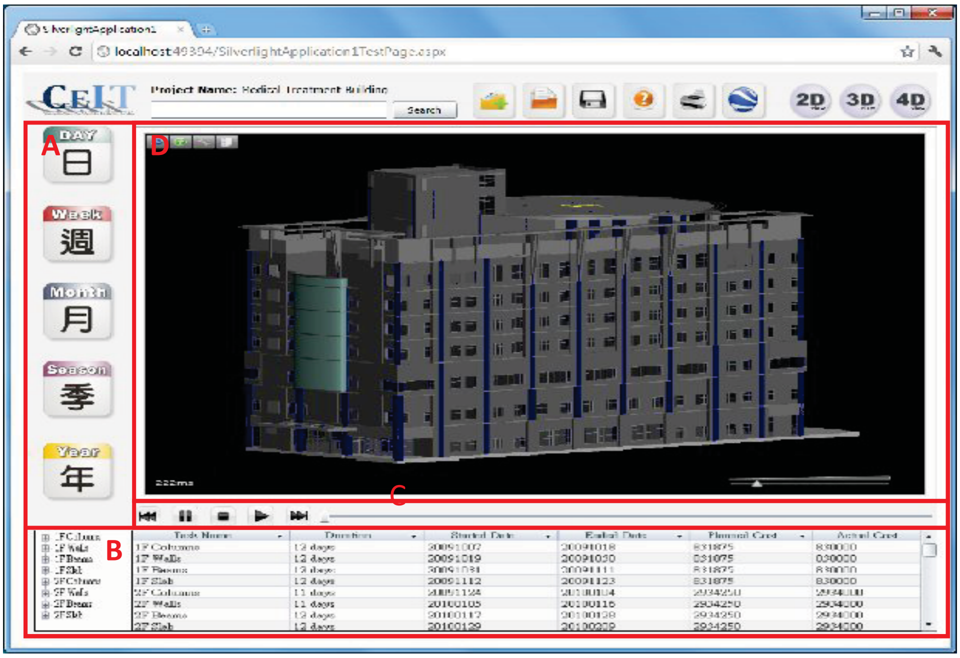


Fig. 6: The interactive GUI of 4D View

6. Conclusions

BIM systems are useful for information integration and visualization. With the trend of rapid technological improvements, the development framework of current BIM systems are moving from "Single-based" to "Host-based", widely referred to as "Cloud Computing" technology. Complementarily, today's multi-touch technology is rapidly forming the basis of many new techniques designed to improve human interactions with computers and mobile devices. These two developments have motivated us to design and implement an interactive GUI for facilitating the manipulation and visualization of information in BIM systems. This paper first reviewed related work in the area of design principles. These design principles have been most important in proposing new design principle of our interactive GUI for BIM systems. In this paper, we proposed seven design principles: (1) Button design should be simple and meaningful, and be intuitively located; (2) System logo and project information should be located at the top-left location; (3) Designers must make frequently-used functions of the BIM system easily accessible with conveniently located buttons; (4) Each page should provide a search toolbar for users to obtain the required data easily and quickly; (5) Providing different view windows to meet different user needs for different applications; (6) Designing interfaces to have similar operations and use similar elements for achieving similar tasks; (7) Providing relevant data on the significant and actual properties of an object. Guided by the above-mentioned design principles, this research implemented an interactive GUI for the Cloud-BIM system that we developed in previous work. There are four major characteristics of this interactive GUI: (1) Button design is simple, meaningful and big, making them easy for touch panel users to manipulate. (2) Three views (2D, 3D and 4D) are provided, and the user can choose their preferred approaches to obtain the required information. (3) Consistency and patterns in UI design, so that users can comfortably learn and familiarize themselves with regular use patterns in manipulating the GUI in the system. (4) Web-based GUI which overcomes many limitations of time and distance and enables users located in disparate places to search and obtain the information they need. An engineering project was used as an example to test and demonstrate the manipulation and visualization using the GUI linked to the Cloud-BIM system.

7. Acknowledgments

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ONTOLOGIES FOR OPTIMIZATION OF STRUCTURAL MODELS

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ABSTRACT: *Evolutionary optimization has become a widely recognized and successfully applied technology in many engineering disciplines. Since computers increase in memory and computation power, more complex optimization problems can be economically solved using approaches like evolutionary strategies or genetic optimization. The software based application of evolutionary optimization techniques to advanced structural engineering problems often suffers from the complexity of the modeling process.*
This paper presents a promising approach which can conquer this complexity in an adequate, high-performance, adaptable and transparent way. It is capable of bridging the gap between abstract modeling principles and complex real world engineering models. The approach is being demonstrated on the optimization and visualization of a reinforced concrete structure.

KEYWORDS: *ontologies, building information modeling, optimization, genetic programming, knowledge based systems, transformation*

1. Preface

Engineering work mainly consists of elaborating solutions for certain design challenges, with the aim to produce the best possible solution, according to the given economic, environmental and technical assumptions. Capacious support by specialized engineering software has become essential to fulfill these demanding challenges.

Modern software systems mainly focus on the support for CAD-drawing, structural analysis and comprehensive simulation. They are complex tools to support the detailed design phase, based on lower levels of abstraction. In contrast to this the most significant design decisions are made during the early, conceptual design phase. During this phase, software based support might be an important step towards “optimal” designing. Support through adequate software systems during this conceptual phase is still rather limited due to several reasons. One of the reasons certainly is the complexity of modeling an engineering problem in higher levels of abstraction, the top-down-modeling approach.

Optimization systems for structures usually need valid simulation models on a lower level of abstraction to evaluate the quality of a certain design. From optimization point of view, detailed models provide a very high number of variables, and due to this a tremendous number of potentially infeasible and inconsistent solutions. As conceptual modeling takes place in higher levels of abstraction, the genotype of the optimization should be an abstract model, not covering details which carry obvious or directly dependent information.

In this paper the authors will present an ontology for abstract representation of building designs, as well as an adaptive way to transform abstract building descriptions into detailed models for simulation and visualization. This paper will contribute an example of a feasible solution to support the modeling part of the optimization process. The approach will be demonstrated on a vivid example of a multi-story office building. It is not the aim of this paper to provide a complete optimization solution or optimization studies on real structures.

2. Principles

2.1 Optimization

The principles of evolutionary optimization are inspired by the Darwinian theory of evolution. A set of individuals produces offspring by reproduction of the best individuals and recombination and mutation of the genotypic information. Applying these principles to engineering problems, it is necessary to formalize the problems using ontology for the genotypic representation. Based on the genotype, each individual will produce a phenotype which is used to evaluate its fitness.

2.2 Genetic Programming

In contrast to "classic" optimization techniques, like evolution strategies or genetic optimization, there is another technology called "genetic programming" (Koza 1992). The original approach of genetic programming was used to generate small structured lisp programs.

Independent from producing lisp programs, the main difference of genetic programming to classical programming technologies is the structured representation of the genotypes. This allows individuals with mutable genotype length. The structured form introduces inherent context awareness when applying genetic operations, which leads to a more efficient optimization process. These advantages predestinate genetic programming for optimizing structural engineering problems. Genetic programming is interesting in context of this paper because it is one of the optimization technologies which can be used to optimize problems with structured genotypes.

2.3 Declarative knowledge based system

Knowledge based systems are generally focused on knowledge representation and knowledge processing. Common knowledge of a certain knowledge domain is acquired and persisted in a knowledge base. An example for the common knowledge concerning structural systems may be a certain design standard. The application of this knowledge occurs on the problem specific knowledge of an instance of the same knowledge domain, which is e.g. a real structural simulation model in abstract or detailed modeling state.

A knowledge based system consists of three main components, which are also shown in Fig. 1:

- A knowledge acquisition component, which is used to acquire the general knowledge in the knowledge base,
- An inference component to apply the knowledge to practical factual knowledge
- And an explanation component to enable the user to investigate the origin of the calculated parameter values

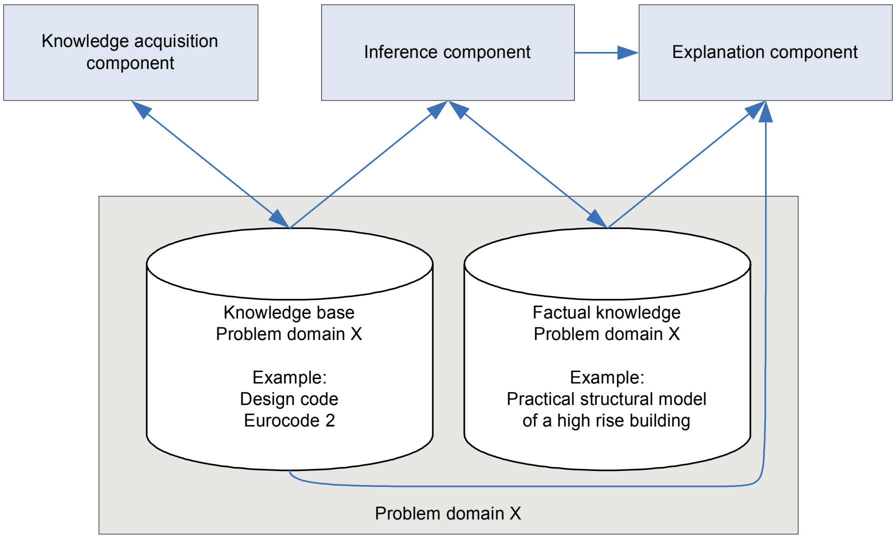

Fig. 1: Knowledge based system, basic components

Declarative knowledge consists of loosely linked knowledge elements. There is no predefined order of calculation. The inference process is started by asking for a certain parameter. During the process, possible knowledge elements are identified, which can be used to evaluate the desired parameter. As these elements may require other parameters, the inference process leads to a dynamically back-linked processing. The declarative knowledge based system used for the presented approach is originally based on the *Object Oriented Model of Engineering Design Standards*, as proposed in (Garret 1992).

3. Ontology for Model Representation

An ontology for representation of structures focused on conceptual optimization should involve the information a designer would need to briefly describe his or her building design in a sufficient way. This description does not define single structural elements, at most groups of them. It rather describes the coarse shape, the basic structure and floor layout. Given the information of an abstract design, the human engineer would be able to provide a detailed design using some assumptions and rules. These assumptions and rules include project specific boundaries as well as common engineering practice. This knowledge altogether defines the transformation process from abstract to detailed structural design.

3.1 Ontology Composition

The combination of the previously described knowledge is the base to formulate an ontology for model representation. The information formalized by this ontology should be sufficient to perform a complete optimization process. This ontology is composed of the following units:

- *Environment* — Involves all outer boundaries which are out of scope for optimization due to immutability. For instance the dimensions and area of a structure can be constantly preset, like any other necessary assumption.
- *Abstract design template* — Defines the structure and boundaries of the conceptual and detailed optimization parameters. It provides the base for the ab-

strict structure descriptions (genotypes) generated by the optimization process (e.g. by means of genetic programming).

- *Transformation knowledge* — Covers the domain specific knowledge which together with the environmental information is necessary to automatically generate detailed simulation models based on an abstract design (as a genotype).

3.2 Template

The abstract design has to be formalized using a certain domain specific language. This language uses strictly defined vocabulary and grammar rules. In this project an adapted version of the Backus Naur Form [BNF] is used. This is a Meta language which is also used to precisely define the syntax of programming languages. The adaptation consists of some syntactic simplifications and the direct definition of numeric values, which is essential for engineering systems.

A shortened version of the abstract design template is given in Fig. 2. This template defines an abstract design which follows an xml structure. From technical point of view it is also possible to define the abstract design template using an extended xml schema. In this case any given abstract design can be validated against the xml schema using standardized xml tools and interpreters. This is especially helpful if the abstract design can be produced and manipulated using external software modules.

An instance of an abstract design is shown in the samples section.

```
[S] := [Building]
[Building] := <Building> [Layout] [Floors] [Stiffening] </Building>
[Layout] := <LayoutBasePart [LayoutBasePartShape] /> [LayoutPart n=0..5]
[LayoutPart] := <LayoutPart [LayoutPartShape] />
[LayoutBasePartShape] := [BaseSquare] | [BaseRect] | [BaseCircle] | [BaseEllipse]
[BaseSquare] := shape="Square" x=[LayoutFieldsX] dx=[LayoutDimensionX]
    numberFloors=[LayoutFloorCount]
[BaseRect] := shape="Rect" x=[LayoutFieldsX] y=[LayoutFieldsY] fieldsX=[LayoutFieldsX]
    fieldsY=[LayoutFieldsY] dx=[LayoutDimensionX] dy=[LayoutDimensionY]
    numberFloors=[LayoutFloorCount]
[BaseCircle] := shape="Circle" x=[LayoutFieldsX] rField=[LayoutDimensionX]
    numberSections=[LayoutSectionCount] numberFields=[LayoutFieldsX]
    numberFloors=[LayoutFloorCount]
[BaseEllipse] := shape="Ellipse" x=[LayoutFieldsX] rFieldX=[LayoutDimensionX]
    rFieldY=[LayoutDimensionY] numberSections=[LayoutSectionCount]
    numberFloors=[LayoutFloorCount]
[LayoutPartShape] := [PartSquare] | [PartRect] | [PartCircle] | [PartEllipse]
[PartSquare] := shape="Square" x=[LayoutFieldsX] position=[LayoutPartPosition]
    fields=[LayoutFieldsX] numberFloors=[LayoutFloorCount]
[PartRect] := shape="Rect" position=[LayoutPartPosition] fieldsX=[LayoutFieldsX]
    fieldsY=[LayoutFieldsY] dFieldOpposite=[LayoutDimensionX]
    numberFloors=[LayoutFloorCount]
[PartCircle] := shape="Circle" position=[LayoutPartPosition]
    numberSections=[LayoutSectionCount] numberFloors=[LayoutFloorCount]
[PartEllipse] := shape="Ellipse" position=[LayoutPartPosition]
    rFieldOpposite=[LayoutDimensionX] numberSections=[LayoutSectionCount]
    numberFloors=[LayoutFloorCount]
[LayoutPartPosition] := north | south | east | west | northEast | northWest | southEast|
    southWest
[LayoutFieldsX] := [Number 4.00;12.00;1.00]
[LayoutFieldsY] := [Number 4.00;12.00;2.00]
[LayoutDimensionX] := [Number 4.00;9.00;0.10]
[LayoutDimensionY] := [Number 4.00;9.00;0.10]
[LayoutFloorCount] := [LayoutFloorCountAll] | [LayoutFloorCountNumber]
[LayoutFloorCountAll] := 0.00
[LayoutFloorCountNumber] := [Number 1.00;9.00;1.00]
```

```
[LayoutSectionCount] := [Number 4.00;20.00;4.00]
[Floors] := <Floors> [FloorGroup 1..4] </Floors>
[FloorGroup] := <FloorGroup count=[FloorCount] dz=[FloorHeight]> [Slabsystem]
    [ColumnsOutsideX] [ColumnsOutsideY] [ColumnsInside] [ColumnsCorner] </FloorGroup>
[FloorCount] := [Number 2.00;20.00;1.00]
[FloorHeight] := [Number 3.00;5.00;0.05]
[Slabsystem] := <SlabSystem type="flat" dz=[SlabHeight] />
[SlabHeight] := [Number 0.20;0.40;0.01]
[ColumnsOutsideX] := <ColumnsOutsideX [Column] />
[ColumnsOutsideY] := <ColumnsOutsideY [Column] />
[ColumnsCorner] := <ColumnsCorner [Column] />
[ColumnsInside] := <ColumnsInside [Column] />
[Column] := type=[ColumnType] dx=[ColumnDimension]
[ColumnType] := "square" | "circle"
[ColumnDimension] := [Number 0.20;0.90;0.01]
[Stiffening]:= <Stiffening> [StiffeningElement] </Stiffening>
[StiffeningElement] := [ShearWall] | [ShearWallPair]
[ShearWall] := <ShearWall alignment=[ShearAlignment] fieldX=[ShearFieldX]
    fieldY=[ShearFieldY] numberFields=[ShearFields] dy=[ShearWallDy] startFloor=1.00
    numberFloors=[ShearFloors]
[ShearWallPair] := <ShearWall alignment=[ShearAlignment] fieldX=[ShearFieldX]
    fieldY=[ShearFieldY] numberFields=[ShearFields] dy=[ShearWallDy] startFloor=1.00
    numberFloors=[ShearFloors]
[ShearFieldX] := [Number 1.00;10.00;1.00]
[ShearFieldY] := [Number 1.00;10.00;1.00]
[ShearFields] := [Number 1.00;3.00;1.00]
[ShearWallDy] := [Number 0.20;0.50;0.01]
[ShearFloors] := [Number 0.00;12.00;1.00]
```

Fig. 2: Abstract design template

3.3 Knowledge based transformation process

For the purpose of visualization, and usually also for optimization, it is necessary to have a valid and detailed simulation model. An abstract description of a building has to be transformed into a more detailed form of representation to produce a simulation model. For practical use the transformation process has to be very adaptive to support a broad variety of engineering problems.

The transformation process uses a knowledge based approach. This enables the user to completely control and adopt the transformation process according to the given optimization problem. Also it is possible to introduce new optimization parameters into the abstract design template, which are interpreted using knowledge based rules. These parameters then can be used to control additional design variables in the detailed model.

Transformation performs three major steps:

1. **Creation of a floor layout meta-model:** To define the coarse layout and construction axes, the inference process considers the layout information of the abstract building description to produce a two dimensional floor layout. The floor layout involves possible locations for structural elements in all or any of the structures floors, so it defines the maximum of all possible locations. Unused locations in parts of the floors may be left out during the element production process.
2. **Extension to three-dimensional meta-model:** The vertical extension of the meta model has to be generated using information about the floors and groups of floors.
3. **Generation of structural elements:** The inference process iterates over edges and nodes of the meta model. On each of these locations specific design rules are applied. These rules decide if and which types of structural elements are generated on a certain location. Also the dimensions are evaluated using knowledge based design rules.

4. SAMPLE

The following sample demonstrates the described concepts on a reinforced concrete structure. In this sample a surrounding optimization process is assumed, which produces individuals in form of their genotypes. Since the genotype used in this context is a structured text, a promising optimization approach to produce this genotype is genetic programming. There are other technologies to produce structured genotypes, so genetic programming and optimization in general should be seen as an example of application only. Beyond optimization, the described principle can be applied to a number of other modeling purposes.

4.1 Abstract design

The abstract design produced by the surrounding optimization system has to fulfill the abstract design template shown in Fig. 1. An abstract design following this template is shown in Fig. 3. It contains an xml-structure, which hierarchically defines a building structure with its necessary parts.

```
<Building>
  <Layout>
   <LayoutBasePart shape=”Rect” x=7.00 y=6.00 dx=5.00 dy=5.00 numberFloors=0.00 />
   <LayoutPart shape=”Circle” position="east" numberSections=12.00 numberFloors=8.00/>
  </Layout>
  <Floors>
    <FloorGroup count=6.00 dz=3.50>
      <SlabSystem type="flat" dz=0.22 />
      <ColumnsOutsideX type="square" dx=0.30 />
      <ColumnsOutsideY type="square" dx=0.30 />
      <ColumnsInside type="square" dx=0.30 />
      <ColumnsCorner type="square" dx=0.30 />
    </FloorGroup>
    <FloorGroup count=3.00 dz=4.50>
      <SlabSystem type="flat" dz=0.20 />
      <ColumnsOutsideX type="square" dx=0.30 />
      <ColumnsOutsideY type="square" dx=0.30 />
      <ColumnsInside type="square" dx=0.30 />
      <ColumnsCorner type="square" dx=0.30 />
    </FloorGroup>
  </Floors>
  <Stiffening>
    <ShearWallPair alignment="x" fieldX=2.00 fieldY=2.00 numberFields=1.00 dy=0.25
     startFloor=1.00 numberFloors=7.00 />
    <ShearWallPair alignment="x" fieldX=3.00 fieldY=2.00 numberFields=1.00 dy=0.25
     startFloor=1.00 numberFloors=0.00 />
    <ShearWall alignment="y" fieldX=8.00 fieldY=3.00 numberFields=2.00 dy=0.25
     startFloor=1.00 numberFloors=9.00 />
  </Stiffening>
</Building>
```

Fig. 3: Abstract design

The first section starting at tag ‹Layout› describes information about the layout of the two-dimensional floor meta model. The layout contains one base layout element (ending with “BasePart”) and additional part elements, which are attached to the base element. In this instance the base layout is a rectangular, regular grid. The number of floors is 0, which means “unlimited”. The actual floors are defined by the following groups of floors. The additional layout part is a circle, which has to be attached to the base grid on the eastern side. The circle is split into twelve sections, and its elevation ends at the eighth floor.

The next section ‹Floors› defines single floors of groups of them. The first group has a number of six floors and a raw height of 3.50 m. The floor layout also contains information about structural elements, the slab system and the columns. Columns are grouped together according to expected similarities in stress resultants.

The section ‹Stiffening› contains stiffening elements like cores or walls, which span multiple floors. For reasons of symmetry some of these elements can also be defined in pairs, which results in a mirroring of the elements to the opposite side of the current layout.

4.2 Transformation Process

4.2.1 Step 1: Creation of a floor layout meta-model

Interpretation of the layout section of the abstract design template leads to formalization of the basic layout elements (Fig. 4). In this step the inference process applies general design rules, which each can lead to a certain geometric shape of a predefined shape set. The parameters of the shapes (e.g. number of fields in x- and y-direction, field width for a rectangular grid) are used from the layout element description. So basically in this first step the inference process performs nothing more than a mapping between the domain specific language and the actual geometrical generation task. The advantage of the knowledge based definition is the possibility to introduce certain rules, calculations and transformations for single parameters.

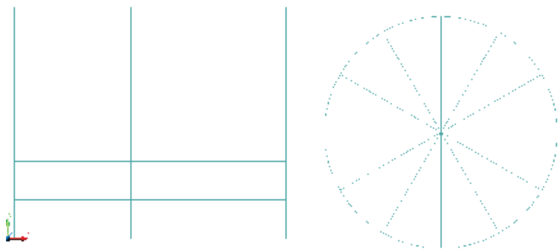

Fig. 4: Basic layout elements

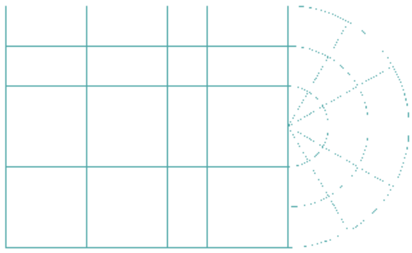

Fig. 5: Layout aligning

In Fig. 5 the generated shapes are merged using the defined merging information, in this case the location "east". In this simple example the shape "circle" always connects "center" to "center of edge", so there is no more information required for the merging process. To allow more complex designs, the position and grid connections could be controlled using additional parameters.

4.2.2 Step 2: Extension to three-dimensional meta-model

In the next step the single floors and groups of floors are used to elevate the meta model into the third dimension. In Fig. 6 the vertical connections are generated. In General vertical connections are located on all intersection points of the meta layout. Later they provide possible locations for columns and walls. This process is repeated for every single floor. In the same way, groups of floors produce the desired number of single floors on top of each other.

The final meta model is shown in Fig. 7. The two different groups of floors are drawn in different colors to separate them optically.

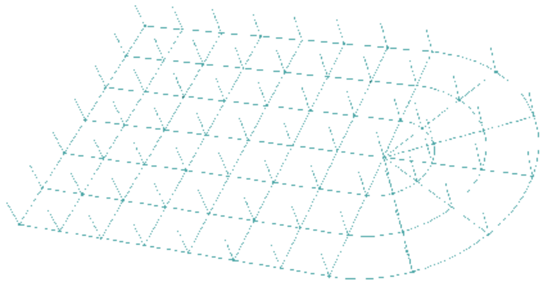

Fig. 6: Single floor elevation

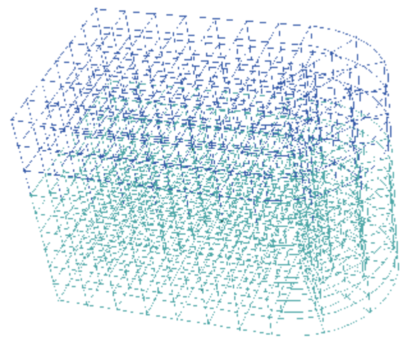

Fig. 7: Final meta model

4.2.3 Step 3: Generation of structural elements

After generation of the meta model, the possible locations for structural elements are defined. The inference process starts to iterate over all edges and nodes of the meta model to apply a set of design rules. Each of the rules results (in case it is applicable) in generation of an appropriate structural element.

An example of a knowledge based design rule for columns is shown in Fig. 8. The rule is applied to any edge of the meta model. The first part of the design rule is the application rule. This rule involves two parameters: The orientation of the current edge (for columns usually in vertical direction) and the floor compared to the current layout area. If the edge is not vertically aligned, no column will be created. Same appears for floors above a certain floor number, which has been limited by the current layout element.

```
If (currentEdge.orientation=z and LayoutPart.numberFloors>=currentFloor.number) then
     applicable=true;
If (currentEdge.isOutsideX and currentEdge.isOutsideY) then
     columnTemplate=currentFloor.ColumnsCorner
else if (currentEdge.isOutsideX) then columnTemplate=currentFloor.ColumnsOutsideX
else if (currentEdge.isOutsideY) then columnTemplate=currentFloor.ColumnsOutsideY
else columnTemplate=currentFloor.ColumnsInside
```

Fig. 8: Design rule for the column design

The second part defines which template section has to be used to define the column dimensions. It may be helpful to have leaner columns on outside areas and corners than on the inside parts. The selection which area represents which part of the layout is defined by geometric properties of the layout, which may themselves being calculated through single knowledge based rules.

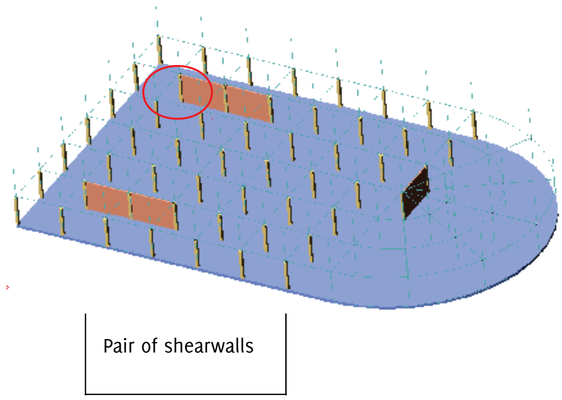

Fig. 9: Structural element generation

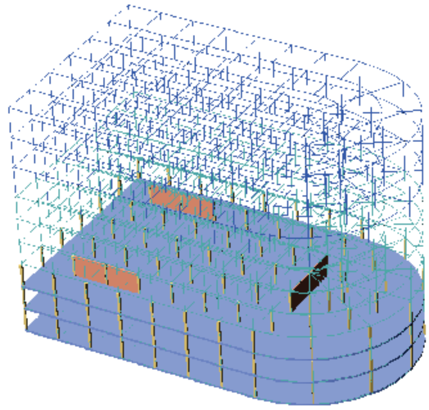

Fig. 10: Structural element generation on third floor

An idea of the element generation process is given in Fig. 9 and 10. Easily visible elements are the stiffening walls. The abstract design contains two pairs of walls. These pairs do not describe adjacent walls, but walls which form a symmetric counterpart as marked in Fig. 9. Other possible types of stiffening elements are frames and cores. Definition of these elements would take place in the abstract template, including the appropriate numerical and logical parameters to allow their occurring in the abstract design. As the resulting detailed structures are composed of standard elements like walls, beams and columns, the extension of the transformation process is limited to the definition of corresponding knowledge based rules. This allows the extension of the ontology solely through the user, without changing the underlying application software.

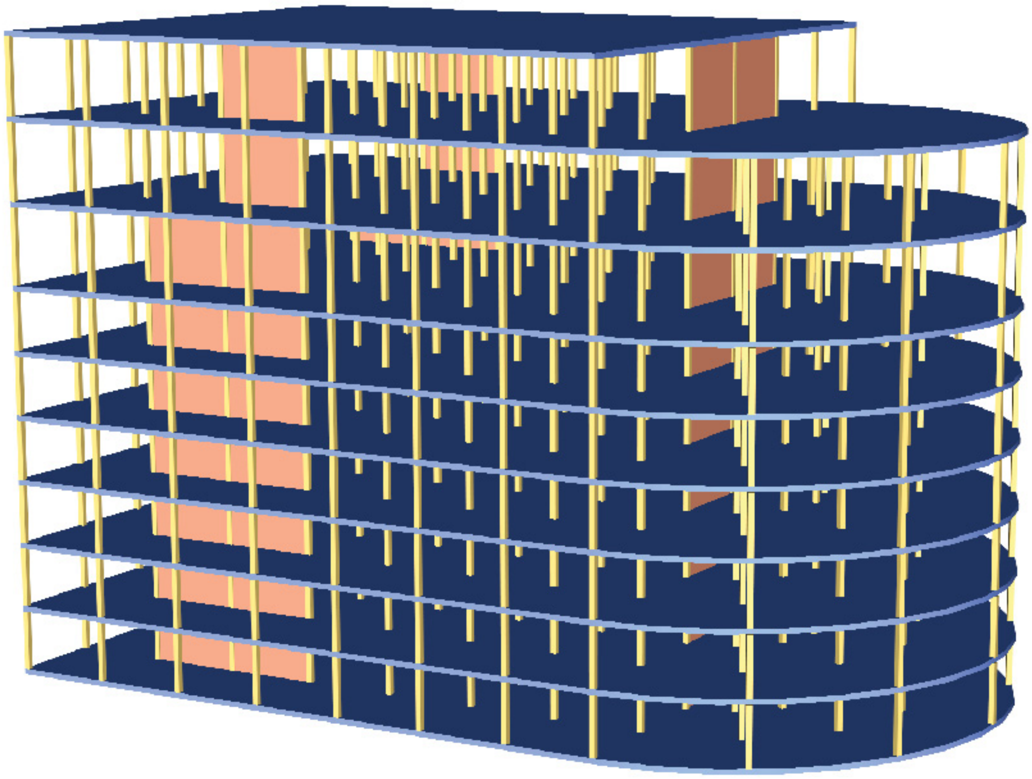

Fig. 11: Final structural model

The final detailed model of the described sample is shown in Fig. 11. The first Pair of shear walls is limited to the lower eight floors, which can be realized on the top left part of the drawing. On the top right the result of the column design rule is visible. Since the circle layout part stops at floor eight, the columns above are not generated. Also there is no covering slab. So it is possible to produce different occurrences of floors using knowledge based rules, even if the topologic model defines identical element locations for all floors.

5. Conclusions

In this paper the authors presented a technology to formalize conceptual and detailed structural models using a goal oriented ontology for different purpose, for instance in context of an optimization system. The described approach can be applied and adopted to a vast variety of designing challenges. Precondition for the successful application is the abstract descriptiveness of the system which has to be modeled. Furthermore there has to be a well-defined way to interpret the abstract description for transformation into the desired detailed model.

The high level of adaptability is realized by the use of a template based approach in conjunction with a knowledge based system. The template based approach allows the user to precisely define an abstract design template and its characteristic and limits. Furthermore it enables adding own optimization variables. The transformation process is controlled by knowledge based rules and formulas. This again allows precise control over the transformation process, the interpretation of the abstract design and the creation of structural elements.

6 Rerefences

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DEVELOPMENT OF A BIM-BASED FRAMEWORK FOR THE FENESTRATION INDUSTRY

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ABSTRACT: *Design, fabrication, installation, and maintenance of curtain walls are challenging tasks (Ma et al. 2005). This is mainly due to the irregular geometry, size, and aggressive pace of today's buildings. The situation is exacerbated due to the lack of communication between participating stakeholders (Ikerd, 2009). Therefore, improvement of communication among the building owner, glazing contractor, glazing system supplier, architect, structural engineer, general contractor, mechanical engineer, curtain wall consultant, façade engineer, and facility manager is essential to assist the design of more sophisticated curtain walls, to proactively solve fabrication and fit-up issues virtually before curtain walls are physically built, and to maintain their functionalities. Building Information Modeling (BIM) is an emerging technology that has profoundly transformed the building industry by enabling exchange of information during a building's life-cycle from inception onward (U.S. GSA, 2007). While BIM has gained significant momentum in the building industry, its implementation in the fenestration industry is sparse to nonexistent. This paper will review some of the current barriers to implementing BIM in the fenestration industry. Then, a framework for utilizing BIM to address the aforementioned issues will be developed, and how this framework can facilitate better design, fabrication, installation, and maintenance of curtain walls will be presented. Finally, conclusions will be drawn and suggestions for further avenues of research will be provided.*

KEYWORDS: *Fenestration industry; BIM-based framework; Coordinated design; Visual construction; Integrated Safety control; Sustainable development*

1. Introduction

Since the middle of the 19^{th} century, the development and application of structural steel and reinforced concrete allow the replacement of the exterior load bearing walls with structural columns. Thus the entire outer covering of a building can be built with non-structural materials. When the most common infill type, glass, is used as the outer covering, namely the glass curtain wall, the advantages are multi-fold: the added aesthetic value, enhanced usage of natural light, a greater human comfort level, and improved building energy performance. More recently, however, new driving forces have made design, fabrication, installation, and maintenance of glass curtain walls challenging tasks: irregular geometry, size, and aggressive pace of today's buildings. Furthermore, the maintenance of numerous curtain wall buildings which face the potential problems such as material aging and glass falling is critical (Patrick, 2003). There is a need for a holistic approach to address these issues that the fenestration industry is facing.

The objective of this paper is to provide practitioners in the fenestration industry, glazers, with an integrated framework that handles the aforementioned issues in commercial buildings. To do this, the current advances in glass curtain wall technology and evaluation tools must be understood. Like other trades in the construction industry, the fundamental barrier in the fenestration industry is the lack of information and knowledge, and the lack of evaluation tools, particularly at the early design stage, that allow the different stakeholders involved to quickly comprehend complex and often times interrelated building issues (Phelps et al., 2008). Therefore, improvement of communication among the building owner, glazing contractor, glazing system supplier, architect, structural engineer, general contractor, mechanical engineer, curtain wall consultant, façade engineer, and facility manager is essential to assist the design of more sophisticated curtain walls, to proactively solve fabrication and fit-up issues virtually before curtain walls are physically built, and to maintain their functionalities.

Building Information Modeling (BIM) is an emerging technology that has profoundly transformed the building industry by enabling exchange of information during a building's life-cycle from inception onward (U.S. GSA, 2007). The basic premise of the BIM process is to create a building virtually, prior to building it physically, in order to solve for design, fabrication, constructability, and maintenance issues, and simulate and analyze potential impacts. The core of BIM is an authoritative building information model. This model is a digital representation of the physical and functional characteristics of a building. Using this BIM model, collaboration by different stakeholders at different phases of the life cycle of a building is possible during the modeling process, which usually occurs during the early conceptual design phase. As an enabling catalyst to three major building industry drivers that especially dominate the fenestration industry: sustainable design, lean construction and integrated project delivery (IPD), BIM is claimed to fundamentally change the glass and curtain wall industry before 2015 (Ikerd, 2009). However, while BIM has gained significant momentum in the building industry, its implementation in the fenestration industry is sparse to nonexistent.

2. Related Work

Several case studies have been found in this field. In 2009, BIM was implemented in early design process of a 52,000 sq ft. (4,830 sq m.) synagogue and community center in evaluating the glass curtain wall design (Eastman and Kuo, 2009). The BIM model was used for structural analysis, thermal analysis, and visual and performance mock-ups. And a workflow was developed for small-scale curtain wall projects (Figures 1-2).

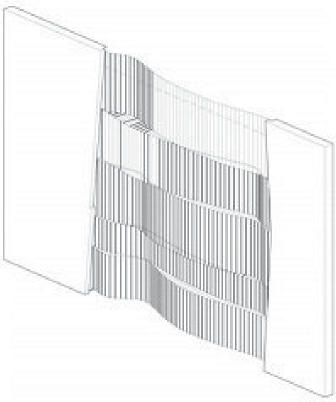

Fig. 1: Diagram Model
Photo courtesy of Eastman, 2009

Fig. 2: Inside of Glass Curtain Wall
Photo courtesy of Eastman, 2009

In 2011, Skanska installed a curtain wall on a 230,000 sq ft. (21,370 sq m.) library with a glass curtain wall that is 300-ft long and 50-ft high (15,000 sq ft./1,400 sq m.). BIM was used to track wall panels - when they are fabricated, packed, shipped, and installed (Figures 3-4).

Fig. 3: James B. Hunt Jr. Library
Photo courtesy of www.lib.ncsu.edu

Fig. 4: Skyline Reading Room
Photo courtesy of www.lib.ncsu.edu

The challenges of installing the flexible cable network based glass curtain wall of Shanghai Oriental Art Center (427,262 sq ft./39,694 sq m.) (Figures 5-6) were discussed by Jin et al. (2005). The complex outer envelope coupled with relatively small structural rigidity of the cable network made precise installation of the glass curtain wall a difficult task. Differing construction sequences result in differing internal distresses and deformations in structural components; thus selecting an ideal construction sequence is essential to assure non-stress installation of glass and thus prevent premature stress and/or strain failure during installation.

Fig. 5: Shanghai Oriental Art Center
Photo courtesy of www.cityweekend.com.cn

Fig. 6: Close-up of Glass Curtain Wall
Photo courtesy of Jinming Ma

Finite Element Analysis (FEA) of the steel shell of Beijing National Grand Theater indicated that the construction sequence was one of the determining factors to accurate and safe installation of the structural components, a precondition of successful installation of the glass curtain wall covering the entire outer surface of the theatre (Wu, et al., 2005) (Figures 7-8).

Fig. 7: Beijing National Grand Theater

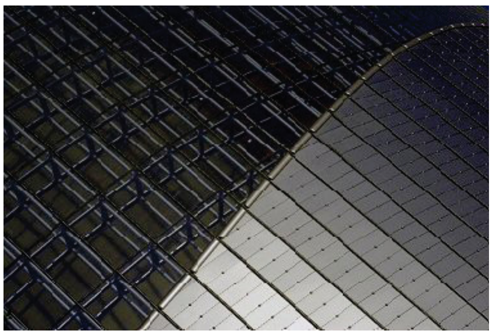

Fig. 8: Close-up of Glass Curtain Wall

Photo courtesy of http://commons.wikimedia.org/wiki/Category:National_Centre_for_the_Performing_Arts_(China)

In 2009, Fang et al. presented several technologies to build a super-tension prestressed single layered cable net serving as the structural support for the glass curtain wall of China Maritime Museum, a 500,000 sq ft. (46,400 sq m.) structure. To achieve engineering tolerance requirements, FEA was conducted, and three methods were used to determine the locations of preembedded parts of the cable net, including two different projection methods and the axis replacement method. Temperature variations and construction sequence of horizontal/vertical cables were found to be prominent factors affecting accurate installation of the glass curtain wall (Figures 9-10).

These studies have shown different levels of efforts in applying advanced technologies, including FEA, computer simulations, and BIM, to installation of the structural frame and glass curtain walls. However, few studies have been conducted to investigate design, fabrication, and maintenance of glass curtain walls using these technologies.

Fig. 9: China Maritime Museum ***Fig. 10: Close-up of Glass Curtain Wall***

Photo courtesy of http://www.gmp-architekten.de/en/projects/maritime-museum.html

3. Proposed Frame Work

The proposed BIM-based framework holistically addresses BIM model development, design, fabrication, installation, and maintenance of glass curtain walls.

3.1.1 BIM Model Development

Most likely the initial BIM models are developed by the architects and specialty consulting firms. These models are used to exchange information among stakeholders during the project's life-cycle from inception onward. Practitioners in the fenestration industry, glaziers, can further refine the initial BIM model to generate a BIM model just for curtain walls. For example, anchor points and connections to the structure can be added to the initial BIM model, which will help the glazing subcontractor to conduct quantity take-offs, price field labor, and field installation. Another example is to link specifications and other drawings to model geometry. When a segment of mullion is selected in the model, users can not only view the curtain wall specification, but also all the related specifications, including sealants, insulation, doors, glass, etc. This glass curtain wall specific BIM model will be really beneficial to glazing subcontractors in their development later.

3.1.2 Parametric Modeling

BIM models are parametric models. Different from traditional 3D modeling technologies which require manual adjustments of every aspect of an objective's geometry; parametric modeling allows the objects in a BIM model to automatically update according to changing contexts. For example, in the window schedule, changing the size of 24”x48” windows to 36”x72” will update all 24”x48” windows, and all affected floor plans, sections, elevations and walls automatically. This is because in parametric modeling, instead of creating an instance of an objective, users define relations and rules, such as attached to, parallel to, and distance from, to control objectives. It is these relations and rules that make the automatic update possible.

Parametric modeling is essential to glaziers. As the outer cover of a building, the curtain wall should change its geometry with the structural frame. A curtail wall BIM enables this design change process automatic, minimizing repetitive manual adjustments for designers and chances of making errors.

3.1.3 Design

3.1.3.1 Structural Analysis

The curtain wall BIM model can export the structural information, typically the wireframe of the structural frame, to analysis software often used by designers. For complex buildings, FEA will be conducted to analyze structural performance under differing temperatures and external loads during construction. The FEA results can be used to select appropriate sizes of structural elements and determine the ideal construction sequence.

Interoperability is critical to seamlessly transfer necessary from the BIM model to the structural analysis software. Industry Foundation Classes (IFC) can be used as the bridging language because of its open specification and its ability to describe building and construction industry data.

3.1.3.2 Energy Performance Analysis

Heat flows through curtain wall assemblies directly affects a building's energy performance. Necessary data needed to perform energy analyses can be imported from the curtain wall BIM model to computer programs, such as Window 6.0, RADIANCE, Daylighting and Electric Lighting Simulation Engine (Delight), EnergyPlus, to simulate thermal performance of the entire curtain wall. Designers can then use the results to select different types of glass and assemblies.

3.1.3.3 Cost Analysis

The curtain wall BIM can easily generate a complete material list, including fasteners, glass sizes, linear footage of frame members, and finish square footages. These quantities can be used to develop construction cost reports for the owner, architects, and engineers. Design adjustments will be made to achieve overall cost goals.

3.1.3.4 Key Design Considerations

Technology, economy, and environmental and societal factors are key considerations of curtain wall designs. During the conceptual design phase, building form, glass materials, scale, and plan layout should be studied to ensure aesthetics, economy, and safety. During the structural design phase, all components of the curtain wall system should be chosen through calculating and analyzing, to meet the requirements of strength, deformation and stability. Redundancy design is a better way to guarantee structural integrity, which allows designers to use residual strength of structural panels to control cracks. During the configuration design phase, special attention should be given to ductility and safety. Configurations with definite performance of fireproof or waterproof should be designed.

3.1.4 Fabrication

Unlike regular buildings, buildings with complex curtain walls require fabrication of engineered-to-order (ETO) components. Fabrication with traditional 2D CAD is error-prone. BIM allows "virtual construction" of components by providing data for pre-fabrication. Then error-free data can be used for the automated manufacturing process. In practice, once the glass curtain wall BIM model has been finalized with sufficient details, it can be used to extract digital information of parts, assemblies, and sub-assemblies directly sending to the Computer Numerical Control (CNC) machine for fabrication. Meanwhile, fabrication drawings for the facade can be generated directly from the BIM model. The traditional way of using 2D CAD drawings for fabrication is no longer needed.

3.1.5 Installation

3.1.5.1 Clash Detection

During a traditional design-construction process, often time conflicts will not be discovered until components are installed in the field. BIM offers an innovative technology, clash detection, to locate potential conflicts from the virtual model before the building is physically built. Thus greater cost savings and a safer construction site can be achieved. Clash detection involves pre-assembling all components in a BIM model according to a predefined construction sequence, to identify physical and spatial conflicts automatically and to generate reports to the users. Using these reports, designers can change sizes of components; contractors can change orders the components be built. The updated BIM model can go through iterations of virtual mock-ups until the best design is found. The virtual mock-up technology can be used by glaziers through the application of the curtain wall BIM model to identify the following coordination errors: hard clash, a physical clash between two components; soft clash, when two components are placed too close to each other; and constructability issues.

3.1.5.2 Virtual Mock-Up

There are two forms of curtain walls: normal form which is flat, and special form which is curve. Normal form has regular shapes and is easy for construction; while special form is more difficult for surveying, locating and installation. A curtain wall BIM model can provide the position of each component and avoid deviation accumulation. According to the time-varing characteristic of curtain wall during the construction process, it is important to apply a 4D technique, 3D plus time, to ensure at accurate construction.

The 4D technique is embedded in BIM. Using 4D, glaziers can virtually simulate the construction schedule for the quality control purpose. Different from regular construction, affected by temperature fluctuation, changing external loads and human factors, condition for install curtain walls may be different from the initial design. It will be adverse to project quality and safety if the differences exceed a certain extent. A virtual mock-up provides designers with support reactions, components' inner force, and deformation of glass panel, truss and connection between the curtain wall and building structure. Any situation deviate from the initial design will be analyzed, and mocked up virtually again until the differences are within an acceptable range.

3.1.6 Maintenance

3.1.6.1 Routine Maintenance

A curtain wall BIM model contains all necessary for routine maintenance. Facility managers can find manufacturing and installation information on materials used in the project, for example, specifications, purchase date, prices, and life spans, to generate maintenance schedules and to place purchase orders.

3.1.6.2 Preventive Maintenance

A curtain wall system deteriorates over time. If not well maintained, an aged curtain wall system can have severe consequences, including structural failure, glass or component falling, leakage, glass crack, material erosion, and sealant aging. During an earthquake or a hurricane, broken glass may obstruct road and hinder people from escaping and being rescued.

BIM's analytical function can be used to assess the condition of a curtain wall system; from which preventive maintenance strategies can be developed. For example, falling glass is usually the final result of damage. When structure displacement occurs, a curtain wall which attaches to building structure will also deform, and the glass will be in tensile, being extruded or twisted at the same time. When the resulting load is larger than the resist force of glass, crack will appear and develop till fracture. So the process of glass damage can be divided into three stages: normal using, crack developing and glass falling (Figure 11). Using the BIM model, digital simulated analysis under random loads of each glass panel can be conducted. The origin of panel cracks, the trend and timing of cracks can be found, and the potential position of panel crack can be located and the possibility of falling glass can be estimated. Based on these findings, facility managers can take appropriate actions to prevent these failures from happening.

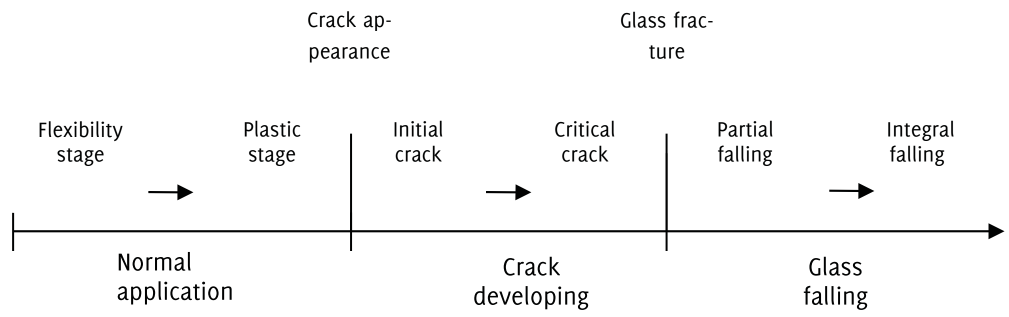

Fig. 11: Damage Process of Glass

3.1.7 Proposed BIM-Based Framework

As an attempt to synthesize past research and this study, a suggested workflow for a BIM course is proposed (Figure 12).

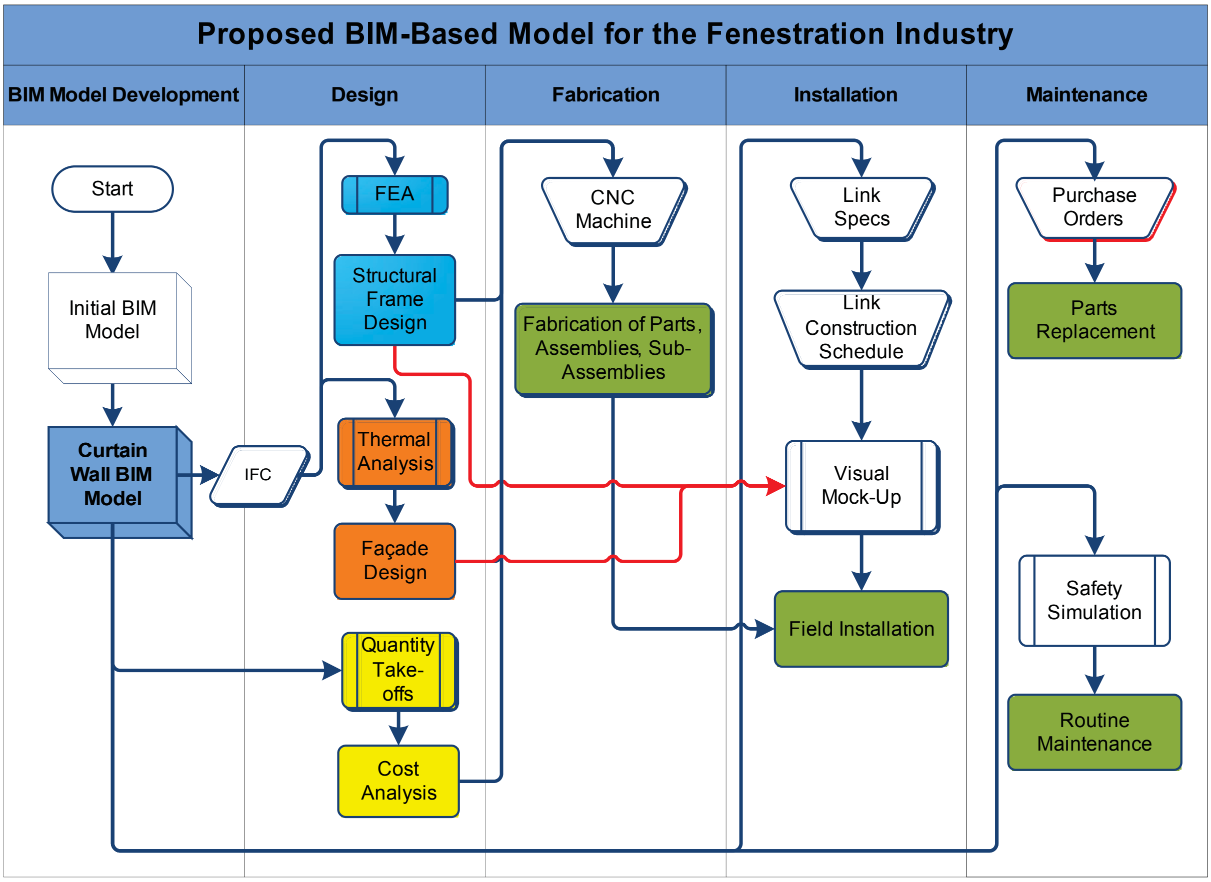

Fig. 12: Proposed BIM-based Workflow for the Fenestration Industry

4. Conclusions and Recommendations

The BIM process is a key to solve problems stemming from the fenestration industry – the lack of communication between glaziers. Based on findings of past studies on curtain wall construction, a BIM-based framework for curtain wall construction is proposed. This framework can effectively address design, fabrication, installation, and maintenance of glass curtail walls. The implementation of this framework is expected to be beneficial to glaziers around the world and should help transform the fenestration industry in the very near future.

Suggested future research areas include: (1) to focus more on success case studies of using BIM in the fenestration industry, which can expedite the adoption of BIM; (2) to investigate how vender developed BIM models can be used for buildings with various complexities, and to what extent. The models should not only be 3D, but also 4D and even 5D to incorporate time and cost factors; and (3) to study the dynamic relationship between glass curtain wall design and sustainability. For example, how to enhance the building efficiency and safety, reduce risks and waste of resources, promote sustainable development of curtain walls, all through the adoption of BIM,.

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VR-BASED CONSTRUCTION SITE CONTROL CENTER

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ABSTRACT: *The development of a physical building control center can support project management and -control to optimize the flow of the complex processes at a construction site. The proposed concept consists of equipping vehicles with sensors and using VR and AR-techniques to visualize this real-time information and allow an immediate adaption to current circumstances. Implementation will show more efficient utilization and enhanced cost effectiveness.*
The requirement analysis starts by identifying relevant content to be presented in VR and AR. The instrument chosen was interview. The second step is to work out the necessary way of computing, viewing and manipulating this data. Finally a hardware setting is designed that would probably fulfill the derived requirements.
The interview results are given below. These results as well as following conclusions about interaction both at control center level and at on-site use, are elaborated and also introduced. Appropriate hardware configurations in terms of interaction and practical feasibility are derived, and the basis for an implementation is established.

KEYWORDS: *virtual reality, augmented reality, control center, process management, optimization, construction site, information visualization*

1. Introduction

With the development of a physical building control center, project management and control can be supported and the flow of the complex process at a construction site can be optimized. The task is to design a human-computer-interface, which allows simple and secure handling even at complex building processes. “Virtual Reality” (VR) offers a good opportunity for doing so. Secondarily “Augmented Reality” (AR) shall be used to support the construction vehicle driver with additional information within the construction site.

Building and digging works consist of many parallel processes, so that a slight accident or interruption can influence the workflow of a whole chain of building vehicles. This causes delays, cost increase and quality suffering. To avoid or minimize the impact of such an interruption it is necessary to reconsider the working cycle. It is impossible to foresee problems like these during the planning phase so that during the execution phase, tasks like this are handled by a participant, who is responsible to regain the work flow. Through imperfect information a reliable base of decision-making is missing, as a consequence vehicles act inefficient or nonproductive.

The key factor is to use proved ideas of the automotive (“digital factor”, (Kuehn, 2006)) and manufacturing industry (“multi agent technology”, (Bergmann, 2010; Dangelmaier, 2009)) to develop a new concept for the civil engineering underground. But there are many distinctions between series manufacturing and the building industry: Building projects are unique and a planning and control system does not exist.

The idea is to equip vehicles with sensors and act by means of software agents in teams. They are able to swap information among each other and eventually take further enquiry to a higher control center. The main objective is to get the involved components in continuous flow without any latency or downtime. The result is a more efficient utilization. Using this system, machine drivers shall be optimally supported. In addition, interferences with costs and deadlines can be visualized at the control center thus the construction manager is able to act positive and promptly to troubles.

For these problems the project "AutoBauLog" ("Autonomous control in construction site logistics", (Federal Ministry of Economics and Technology, 2010, Frantzen and Rickers, 2010)) can be used.

Within the AutoBauLog project a requirements analysis identified specific needs within the project's context. The instrument chosen was interview. The requirements analysis always starts by clarifying the relevant object to be presented in VR. The second step is to work out the required way of computing, viewing and manipulating this data. Finally a hardware setting is designed that would probably fulfill the derived requirements. (Whyte, 2001)

2. Control Center Use Case

Conventional control centers consist of instruments, a planning table and communication devices (Pawellek, 2007). Electronic control centers are assembled of capacity disposal and electric planning tables. Incurred information may be accessed and evaluated directly (Kurbel, 2005). But this presented innovative control center makes use of information technology and state-of-the-art sensors to add an additional benefit to a "normal" control center.

The most important task is to provide information. Therefore building vehicles will be arranged with Topcon[1]-sensors. This is not a GPS-receiver like a car sat, but rather a specific technology with increased accuracy. Additional sensors are able to collect the excavator bucket, shield tilting dozer position and orientation exactly. Also technical data like maintenance interval, amount of diesel, engine oil pressure are known, so that a huge data basis exists. In this manner an overview of the entire site can be taken and a direct management is possible.

For example if a long queue of dumpers is recognized while removing binder soil, instructions can be displayed directly to the dumpers' drivers cab to adjust truck disposal. He can add refueling, bring forward his lunch break or be advised to slow down his dumper to rest its' material. As a result all dumpers can drive equally-distributed at the building site and all are in a continuous work flow again.

The control center information does not only show the direct environment but also vehicles working far away, which allows a global and not just a local optimization. Consequences of changes in the flow chart are automatically adjusting the time schedule. The impact will be shown directly. The same applies to the interaction of costs, so the site manager is knowledgeable at his best.

But help of the control center is not always required. Using multi-agent technology, every machine is allocated by a software-representative; as a result intelligent support for the machine driver stands by. For example, if no more dumpers are available, so an excavator is not able to dump the material to be removed.

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[1] Tokyo Optikal Company Nippon, one of the world largest affiliated groups within the field of geodetic surveying instruments

It now has got the alternative to retrieve truck data and get to know where the dumpers are. Optional extra work can be accomplished or more trucks requested.

In case of a simple breakdown or changes of ground conditions, the removal-team arranges itself and adapts its load to new circumstances - without any connection to the control center. Just if it is impossible to finish the task in the given time-frame or rather crossing a threshold, there will be an escalation to the control center layer.

Using VR visualization techniques an ergonomic and intuitive layout is possible, which professionally supports users with a background in construction management and not computer science. A simple, clear display on the basis of firm data allows achieving an established decision.

For the control center the requirements analysis brought following results concerning the necessary aspects to be visualized:

- *terrain and subsoil*: initial DTM (digital terrain model), actual DTM, desired DTM (after end of activities), geometric difference between desired and initial DTM, geometric difference between desired and actual DTM.
- *soil*: type of soil, soil conditions, soil classification (re-usable, sustainable, dump, …), obstacles (e.g. rocks).
- *the structure to be build*: e.g. new road, difference between desired structure and status quo.
- *other structures*: vegetation, brooks, existing human-made structures (e.g. buildings, installations, tunnels, cables, pipes).
- *equipment and resources*: machines according to exact position, status, assignment, performance characteristics, machine data, installed webcams.
- *areas*: area dimensions, type of use, logistics capacity, road condition (trafficability, allowed/feasible by different types of vehicles).
- *infrastructure on construction site*: fuel station, water and gas, external roads, dumps, storage area, signage.
- *activities and processes*: overview of the total project status, with completed, current and future processes and their dependencies. Assignment of current processes with resources and status ("60% done" or "dumper 4 is driving to excavator 2, estimated time of arrival: five minutes")

It is possible to update the production status or the completion date by creating a forecast that is based on real-time data. Short- and middle-term prediction of bottlenecks may also be added. Other information like legal framework or planning documentation should be accessible to brief and support the construction manager and the planning staff. Basically, what is needed is an accuracy in the vertical axis (y-axis) at the structure in mm-range is needed and cm in area (xz-layer). An update of the construction site advance is not necessary more frequently than five to fifteen minutes.

The interaction with this data must allow making cross section cuts, panning, walking, zooming, and jumping to predefined camera positions. Further on there must be information retrieval from machine objects and area objects. The user should be able to open a communication channel to staff on the construction site and to open video streams from webcam installed on the construction site. Alarm messages (e.g. machine breakdown, machine performance permanently too low) need to be recognized and accepted.

It finally came out that a planning table hardware configuration could be very useful to install. It delivers a 2D layout from bird's perspective and a 3D view from inside the field (see figure 1). This allows having a quick overview in the familiar layout style as well as a intuitive 3D insight at the same time. This is also a multi user system (see figure 2).

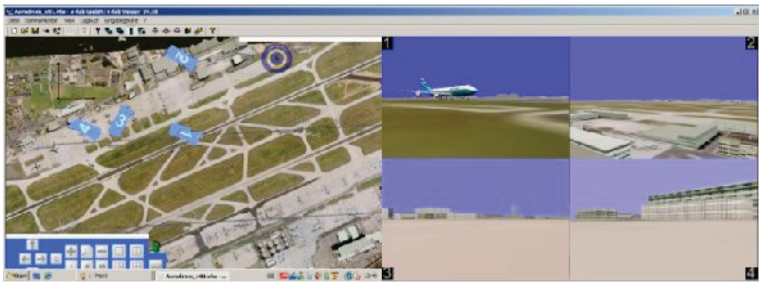

Fig. 1: Planning table for construction site monitoring

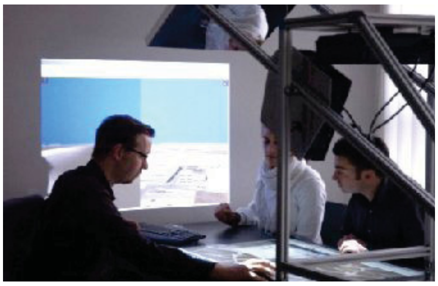

Fig. 2: Use case

3. On-Site Control Use Case

Sanladerer (2008) does notice the benefit of AR for construction sites and recommends the adoption of ergonomic visualization to process-related information, especially for drivers. Shin and Dunston (2008) and Dunston and Shin (2009) also see AR as the adequate technique to optimize processes at construction sites. Workers are able to do their action simpler and more efficient, supported in a comfortable way by visual information, usable in different areas at the building site.

For many building vehicles that are combined with state-of-the-art sensors, lots of application possibilities exist. Some examples are given below.

- *excavator*: visualization of the digging place and geometry or cable or tubes in the earth to present zones of care to the driver (transfer of (Roberts et al., 2002) to construction sites).
- *roller compacter*: visualization of dynamic densification control; the drivers knows at which places he still has to compact and which he has to avoid to prevent overcompaction.
- *tower crane*: illustration of the place of delivery of a load, visualization of jib length and rotation limiting and also accessibility of not yet produced structures in the planning phase (see (Hammad et al., 2009)).
- *general*: using mobile devices by an inspection of a construction site performance data can be embedded context sensitive, working processes visualized and target-performance comparison accomplished.

To realize these use cases, a computing background is necessary. The continuity of 3D-data from the planning to the execution phase has to be available. Media conversion between these phases has to be deleted. The base may be the 5D Initiative (see (Kessoudis, 2008; Zueblin AG, 2009)).

For the on-site use case the requirements analysis brought following results concerning the necessary aspects to be visualized:

- *infrastructure*: display of subsurface infrastructure (e.g. tubes, cables).
- *process support*: for operators of excavator, compacter.

- *comparison digital model vs. reality*: evaluation of the digital model of existing man-made structures on construction site compared to reality.
- *navigation support and geo fencing*: for drivers on construction site.

Options 1 and 2 dropped out due to either a non precise data basis or due to already existing solutions. Options 3 and 4 in contrast are feasible and promise a good benefit.

Different AR hardware settings were analyzed. Head mounted displays and projection AR (onto windscreen) could be interesting in future but seem not to have reached enough practicable status today. Hand held displays on the other hand could be interesting as well as offline AR, which uses digital photographs to be augmented off-site at a desktop PC.

4. Conclusion

The novel construction control center offers a global sight of the construction site. Real-time information is available and allows an optical adaption to current circumstances. Variance comparison in an operating state is the base for efficient project management/control and disposition and adaption of building vehicles to the current situation. In this way cost effectiveness and performance will be enhanced.

Newly developed and adapted VR and AR environments carefully designed for the specific use case, promise good benefits for the control centers and on-site use cases in the future.

5. Acknowledgement

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AUGMENTED URBAN MODEL: BRIDGING THE GAP BETWEEN VIRTUAL AND PHYSICAL MODELS TO SUPPORT URBAN DESIGN

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ABSTRACT: *In architecture and urban planning physical and digital models fulfil different tasks and functions within the design process and are not directly connected. This is due to their largely complementary characteristics and qualities. Whereas physical models are primarily used as a design tool and to represent and communicate a design, digital models also support the evaluation of a design by employing computer-aided analysis and simulation techniques.*
Within the scope of the presented work we analysed the use of the model as an analogue and digital design tool as well as its importance for the work process. In addition, we examined existing tangible user interfaces from the field of architecture and urban design. Based on early projects and approaches in this area such as the metaDESK by Ullmer and Ishii and the Urban Planning Tool Urp by Underkoffler and Ishii we developed a prototype application, the Augmented Urban Model.
The Augmented Urban Model aims to bridge the gap between physical and digital models and their usage in urban design and planning. The objective is furthermore to create a tangible user interface which facilitates interaction with and manipulation of digital data in real space. It combines the qualities of physical and digital models in the work process to facilitate the handling of digital applications and transfers digital data into a spatial context by augmenting the physical model with digital information.
The Augmented Urban Model was realised using current technologies, such as a back projection table and conventional consumer electronics, which enabled us to use and process non-predefined model elements.

KEYWORDS: *architecture, urban planning, physical and digital models, simulation, tangible user interface*

1. Introduction

Just like in any other area of daily life the computer has become an integral part of the work processes in architecture and urban planning. Computer-Aided Design (CAD) and 3D modelling substituted or extended traditional design tools such as drawing, perspective presentation and models. Today computer-aided tools support the development, processing and planning of a design from the initial idea to the completed building.

Whereas drawings and perspectives have been almost completely digitized, digital and physical models coexist within the design and development process, due to their different and partly complimentary characteristics and qualities. The designer employs both and switches between the analogue and digital world as required. In this process, however, the analogue and digital model are two separate models not directly connected with one another.

The work presented in this paper is based on the idea of bridging this procedural gap and connecting physical and digital processes in the scope of an Augmented Urban Model. The architectural model provides the opportunity to build on existing interaction structures and combine the physical-sensual qualities of the analogue model with the advantages of digital models. The Augmented Urban Model is a tangible user interface that supports urban planning in various design phases. Tangible User Interfaces connect and represent virtual data with and in real physical objects or surfaces and support interaction that can be experienced with all the senses. The Augmented Urban Model builds on approaches and early projects in the area of tangible user interfaces that have a similar background, such as the metaDESK by (Ullmer & Ishii, 1997) and the Urban Planning Tool by (Underkoffler & Ishii, 1999).

In chapter 2 of this paper, we provide an overview of physical and digital models, their functions and relevance within the architectural and urban design process. Chapter 3 discusses earlier precursors of tangible user interfaces with a similar background in architecture or urban planning. The Augmented Urban Model, its concept and a prototype application as well as possible scenarios for application are described in chapter 4.

2. The use of the model in architecture and urban planning

In architecture and urban planning models are defined as three-dimensional structures of different scales (Goode, 2009). The present definition of the model differs from its linguistic origin "modello" which was often used in place of "disegno" and could also refer to a drawing (Binding, 1993). The term model can furthermore stand for physical as well as virtual representations (Morris, 2006). In this paper, we distinguish between analogue or physical models that exist in real space and possess a tangible quality, and digital or virtual models that exist in virtual space and which can only be made visible by using an output device such as a screen.

2.1 The physical model

Within the scope of architectural and urban design, physical models are primarily used for visualisation and communication purposes (Dunn, 2007). As such, models are not only small-scale representations of the final design but can also describe conceptual information. The physical model can be seen as a spatial, tangible representation and translation of an abstract idea and drawing (Eissen, 1990). It spatializes an idea and makes it tangible and perceptible. The user can change and manipulate its elements easily and playfully, and observe and evaluate its spatial qualities.

The immediate perception of space is important for understanding architecture and is one of the main advantages of the physical model (Rasmussen, 1980). Formal and spatial problems exist in the same way as they do in the real building. In addition, the model possesses characteristics of the real world such as size, form, colour and texture. As a result, the observer finds it easy to comprehend and decode (Dunn, 2007).

The architect can use the physical model as a creative tool during the design process "to visualize and control spatial aspects" (Eissen, 1990, p. 19; author's translation). Like a sketch it can serve as an experimental tool in order to study interior and exterior form, structure, surface and lighting. Flexible parts make it possible to test alternatives and to change and vary spaces on a small scale (Knoll & Hechinger, 2006). Furthermore the three-dimensional physical model helps to understand complex visual dependencies which cannot easily be perceived in two-dimensional drawings (Dunn, 2007).

2.2 The digital model

A digital model is an internal, digital data model that describes the physical form of a building in the scope of CAD or 3D modelling software programs (Negroponte, 1970). One can differentiate between geometry and building models which are in general created with different software programs and fulfil different functions in the work process (Schneider, 2009). Geometric models are closer to the physical model in form and function whereas building models developed out of the structure of the digital drawing.

Geometric models are models made up of geometrical objects which are generally created with 3D modeling software such as 3ds Max, Maya or Cinema 4D. In the design process they are used to create realistic renderings or animations in order to visualise and communicate a design. Modeling software such as Rhinoceros, and its plug-in Grasshopper, help to develop parametric and algorithmic design solutions using the digital model as a creative tool.

Building models are component-oriented models in which additional and detailed building information such as materials or structural information are stored. So-called CAD programs, such as AutoCAD or ArchiCAD, and also planning software such as Revit and Allplan, are used to create building models. These are typically used for the later detailed planning in which building information modeling (BIM) plays an important role. It facilitates the workflow of planning processes and the exchange of data between different partners (Graphisoft Deutschland GmbH).

Digital models also help us understand and critically evaluate a design solution. Based on a digital model the architect can conduct quantitative analyses to test the efficiency and performance of a specific building solution (Szalapaj, 2001). Analyses and simulations can be used in different phases of the design process. Based on their results, important decisions can be taken regarding the further development of a design (Szalapaj, 2001).

2.3 The urban design context

The work presented here focuses on supporting urban design processes. Urban planning tasks place specific demands on the design process as they are concerned with the development of the physical environment, the "topological constraints for the spatial organization of local society" (Curdes, 1995, p. 10, author's translation). The architect and urban planner cannot cope with complex urban problems without the help of aids such as analyses of the planning area taking into account different criteria (Schwalbach, 2009). The analyses provide an abstract representation of the city which helps the architect to see the task more precisely and provide the basis for further planning.

The design process is composed of several phases and evolves in general from a larger to a smaller scale, i.e. from a rough concept at the scale of the land parcel to a detailed design at the scale of the building. The continuous analysis of an urban design solution and its associated revision are an important part of the process.

In the urban design process, physical models are often employed as a tool and medium. One of the aspects of urban models is the integration of building volumes in their environment and the existing built structure (Knoll & Hechinger, 2006). In addition, they visualize building groups and their relationships to each other as well as how squares and spaces are situated between buildings (Knoll & Hechinger, 2006). In the concept model the designer can explore the spatial distribution and functional arrangement of building masses in their urban context. The working model is used to test alternatives. Designing with a physical model makes it possible to experiment almost playfully with different possible urban arrangements by moving non-detailed volumes in their urban context, i.e. on a terrain model or on a map.

The final design is, however, processed and developed digitally. For this it becomes necessary to digitize or digitally replicate the concept or working model. In turn, in order to evaluate spatial characteristics, the designer has an analogue model built from digital data after working up his or her design. The work process therefore switches between analogue and digital models but they are not interconnected. A procedural gulf exists, i.e. an interruption of the workflow and flow of creativity.

The aim of the Augmented Urban Model is to close this gap and facilitate the dynamic transition between physical and analogue worlds. Furthermore it aims to support the creative and aesthetic as well as functional and analytical work and design processes by connecting physical and digital models via a mutual interface. The concept of the Augmented Urban Model relates to approaches and early projects in the field of Tangible User Interfaces (TUI).

3. Tangible User Interfaces (TUI)

TUIs augment and connect physical objects with digital information. The physical objects very often serve simultaneously as input and as output devices. They consist of an object-related physical and a digital feedback component in the form of visual or auditory feedback (Shaer & Hornecker, 2009). Ullmer (2002) distinguishes between three types of TUIs: interactive surfaces (cf. Reactable Systems; Underkoffler & Ishii, 1999; Ullmer & Ishii, 1997), constructive assemblies (cf. Aish & Noakes, 1984; Frazer, 1995; Raffle et al, 2004) and token + constraint systems (cf. Perlman, 1976).

The development of TUIs is a response to current interaction techniques, which are based on omnipresent input devices such as the mouse and keyboard, as well as graphical user interfaces (GUI), and solve different tasks using the same tools and gesture (Wellner et al, 1993). This is accompanied by a loss of tactile perception and of interactive diversity. Perception is reduced to its visual component, the screen, and interaction to what can be achieved with a mouse or keyboard (Bruns, 1993).

A holistic approach to the perception of and interaction with form and material, however, plays an important role in human actions and comprehension, i.e. the mastery of work processes and building of experience (Bruns, 1993). Studies have shown that rich gestural interaction can enhance creativity (Wang & Nass, 2005). Curbing gestures and movement constricts creative thought processes (Klemmer et al, 2006). Within the scope of a user study that observed the processing of three-dimensional modelling tasks, Kim and Maher (2008) have furthermore shown that TUIs as opposed to GUIs have a positive impact on spatial cognition, which in turn enhances the problem-solving abilities of the user. In addition, the use of TUIs results in more creative solutions and a more experimental workflow.

Although TUIs only recently became an established field of research in the 1990s, their precursors date back to the 1970s and 1980s (Hornecker, 2008). Among those early works are the work of Aish and Frazer who focused on user-centered alternatives for CAD applications. The building block system (Aish, 1979; Aish & Noakes, 1984) is a constructive assembly with which the user can build physical-digital models. Beginning in the late 1970s, Frazer (1995) worked on intelligent, physical modelling systems. These also aimed to enhance and improve the usability of such systems. Several architecture- and urban planning-related TUI projects were also motivated by the aim of improving the visualisation of designs to facilitate better communication with laymen.

An early example of a TUI from the 1990s is the metaDESK and its tangible geospace application in which the user could interact with a map of the MIT campus by using physical icons (Ullmer & Ishii, 1997). The metaDESK is an interactive surface that consisted of a table with plexiglas inlay as a screen onto which the two-dimensional maps were projected. The common interface elements – window, icons, manipulation points, menus and controls – were translated into physical forms. These so-called phycons were used to manipulate the data displayed (Ullmer & Ishii, 1997).

The urban planning tool Urp (Underkoffler & Ishii, 1999) is a similar project that, among other things, used small building models as physical tokens. The building models did not only visualise the respective data but also directly represented it (Shaer & Hornecker, 2009). Simulation software was employed to solve many of the relevant problems in architecture and urban planning such as the calculation of solar altitudes and shadows of buildings at certain dates, wind speed at pedestrian level or reflections off glass facades (Underkoffler & Ishii, 1999). The system dynamically adjusted the digital shadows as the building tokens were moved around on the table. Additional phycons made it possible to change other criteria (Underkoffler & Ishii, 1999).

Illuminating Clay and Sandscape are more recent projects that focus on the analysis and simulation of landscape models. They are organic TUIs made of mouldable materials instead of preset, static objects for interaction. The user adjusts their surface and with it the landscape topography as needed (Piper, Ratti, & Ishii, 2002; Shaer & Hornecker, 2009). A laser scanner scanned the changing surface geometry in real time. The depth image was computed and the resulting digital model formed the basis for different landscape analyses (Piper, Ratti, & Ishii, 2002). The results were projected back onto the model surfaces and were automatically adapted as the surface changed (Ishii et al, 2004).

4. Augmented Urban Model

In "The Architecture Machine", Negroponte (1970) proposes an interface that facilitates direct, fluent and natural interaction between the architect and computer. This interaction does not require specialised knowledge and can take place independently of conventional input devices. Instead the design task is worked on "in the designer's own idiom" (Negroponte, 1970, p. 9). According to Negroponte (1970) this would result in a dynamic dialogue and exchange of ideas between man and machine.

As we have seen in the previous chapter, concepts and projects evolved very early on in the history of TUI that already came close to Negroponte's vision of an architecture machine. These connected physical models and virtual information in different ways. Whereas modular TUIs are suitable for the simulation, analysis or representation of buildings and their parts (see building block system and intelligent physical modelling systems), interactive surfaces are of interest when dealing with urban problems, analyses and simulations (cf. Urp and Illuminating Clay). The Augmented Urban Model also builds on this conceptually as well as technically.

4.1 Concept

As described in chapter 2.3 the Augmented Urban Model aims to facilitate the dynamic transition between physical and analogue models in urban planning processes. Interaction with the Augmented Urban Model is designed to correspond with the process of working with a physical model so that the interface itself recedes into the background leaving the user free to interact. The interface is conceived to allow the user maximum freedom when designing. The designer can use elements of different materials, sizes, forms and colours and place them deliberately on the interactive surface of the Augmented Urban Model.

The tangible manipulation of physical elements of the model provides the conceptual basis for user interaction with the Augmented Urban Model. The physical elements of the urban model exist simultaneously as digital elements of a digital model. They are connected logically so that alterations in the physical model result in the automatic adaptation of the digital model. The user can interact with the model using familiar modes of interaction such as moving or rotating elements, or adding or taking away elements.

The arrangement of physical elements makes it easier to understand spatial relationships between building volumes while the results of analyses and simulations helps by supplying additional relevant planning information. The results of analysis and simulation are projected back onto the interactive surface, augmenting the physical model. The visual and spatial connection of physical and digital information provides a comprehensive picture of the suitability of a design solution. Analysis and simulation results adapt dynamically in response to changes in the physical model.

Markers and touch recognition offer additional means of interaction. Markers make it possible to choose different kinds of analyses and simulations. By touching the interactive surface the user can, for example, select and deselect simulation properties and different kinds of maps.

4.2 Prototype

In the scope of our research we developed a prototype application which was based on a back projection table at the chair of computer science in architecture at the Bauhaus-University Weimar. For the detection and transmission of touch input and the recognition of the fiducials used to identify the markers, we employed the reacTIVision software. The software's TUIO protocol transmitted the detected objects and their tracking information to a laptop which controlled the visual feedback, i.e. the back projection.

The urban planning tool Urp detected physical objects with the help of their respective marker codes. This meant that the geometry of the objects had to be stored along with its marker id in advance. Consequently the system only detected and allowed predefined elements, which constricts the creative design process. Sandscape and Illuminating Clay, however, allowed a surface to be formed and adapted without restrictions. The surface was scanned and its topography processed which offered greater flexibility of interaction as well as better augmented simulations.

Fig. 1: Experimental Set-up

A pre-existing and economical alternative for scanning surfaces is offered by Microsoft's Kinect sensor (Microsoft Deutschland GmbH). Kinect is a novel controller for the Xbox 360 gaming system with which the player can control a game with his body movement and gestures. The Kinect sensor possesses an rgb camera, a depth sensor and a microphone which can detect movement and depth of the whole body, as well as face, gesture and language recognition. In the scope of this project we used the Kinect's depth image for depth detection and object recognition. We connected the sensor via USB to a laptop which interpreted and processed the depth information and finally created the visual output for projection. The experimental set-up can be seen in figure 1. The Kinect is placed above the touch table surface.

We implemented a simple shadow simulation to test the prototype. The application was developed in Visual Studio 2010 using csharp (C#). In addition to the TUIO client for detecting touch-based input and marker events, we used the CLNUI SDK to communicate with the Kinect sensor as well as the OpenCV library to detect the shapes of the objects.

Figure 2 depicts the internal program flow. The Kinect sensor (b) transmits the depth image (c), which is then processed further. With the aid of OpenCV functionality we detected the shape of the objects (d). In the current implementation, object recognition is limited to rectangular elements. The detection of free-form objects is planned for a later extension of the system. From the detected contours and respective depth information, i.e. their height and location, model elements are calculated and stored in a digital model.

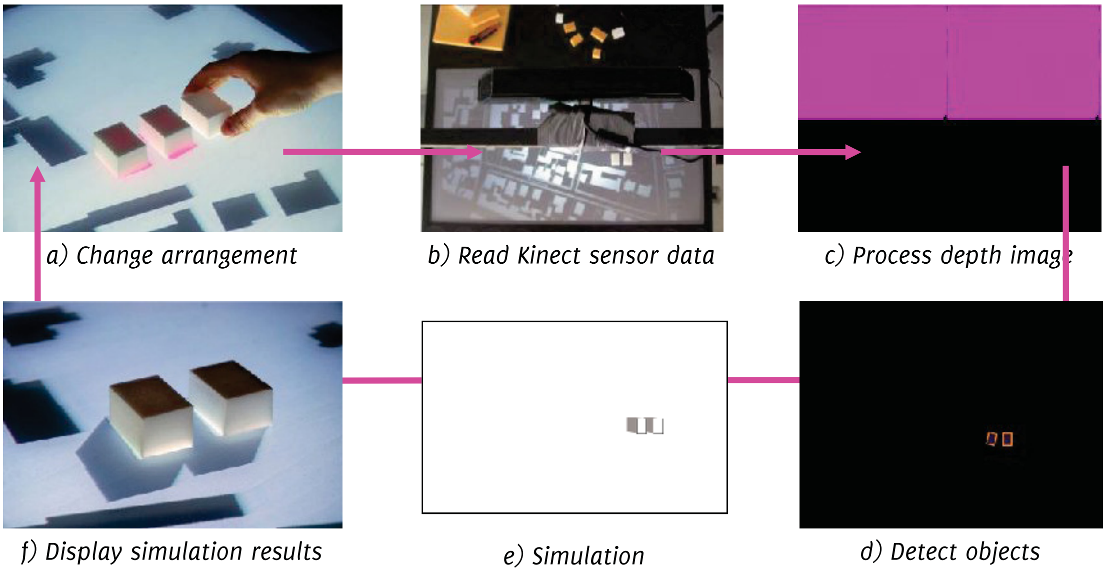

Fig. 2: Schematic program flow

The shadow simulation calculates the shadows cast by the objects (e) based on the map-specific geographic coordinates and the altitude of the sun. The shadow simulation can calculate shadows at a certain date and time, animate shadows over the course of a day or calculate and display annual shadow maps. The results of the simulation are displayed on the interactive surface (f). If the user moves or changes the arrangement of the physical objects (a) while the simulation is running, the system dynamically adjusts the digital model and recalculates the shadows and the graphical output.

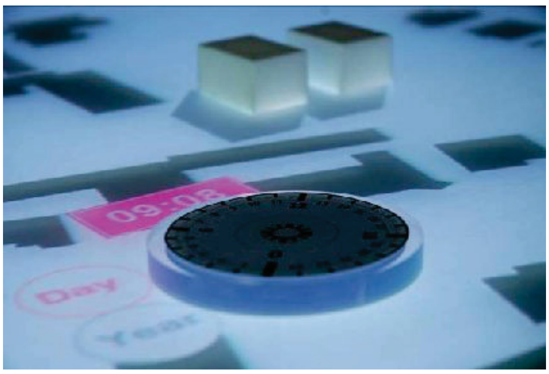

Fig. 3: Shadow simulation in detail

4.3 Additional application scenarios and integration of the Augmented Urban Model into the design process

The Augmented Urban Model can support different stages of the urban design process such as the analysis and development phase and can also serve different purposes such as cooperation and communication between different groups of people concerned in the process.

An analysis of the planning area is the starting point for every urban design task. In the analysis phase the designer collects and prepares information concerning the given task (Curdes, 1995). The analyses are based on observations and perceptions of urban structures as well as the morphology of the city, but also on the interpretation of scientific measurements and data (Schwalbach, 2009).

Maps such as figure-ground plans, topographical maps or estate plans are useful for analysing the area and situating the results. For the qualitative evaluation of existing buildings, urban planners apply layer analyses. In the scope of layer analyses, the planner analyses and portrays functional and spatial aspects on separate layers that augment each other in urban space. The functional and spatial aspects examined include, for example, building, development, transportation, utilization and residential structures (Schwalbach, 2009; Curdes, 1995). In addition to being able to assess the separate criteria independently, their interdependencies are also of special interest as they help to reveal the causes of urban conflicts and undesirable developments.

The visualisation of the results of such analyses plays an important role for evaluation (Schwalbach, 2009). The results are usually charted on a map to show their spatial impact and to locate their characteristics.

Most maps and data are now available digitally. Digital information is collected, managed and analysed in geo information systems, or GIS (Eisenberg & Brombach, 2010). The Augmented Urban Model can be used to display digital information in a spatial context through its interactive surface. As a result, the information once again acquires a map-like character. Furthermore the interactive surface makes it possible to manipulate data by moving, zooming and selecting maps as well as displaying the different layers of analyses.

With the help of these analyses, the designer can then develop preliminary ideas and examine their spatial and functional composition with the help of a physical model. Typically, this takes place using simple blocks made of materials which are easy to form or cut and can be arranged on a map. The Augmented Urban Model builds on the same mode of interaction and therefore helps to support the designer in the early development phases. Its interactive surface displays the urban context in which the physical model can be placed. The interactive surface also makes it possible to change the map or to display additional information, e.g. from the analyses, without affecting the physical model.

The physical layout of the urban solution is scanned and stored digitally. Different versions and alternatives of physical compositions can be saved and retrieved digitally at a later time. As a result, the design process is well documented and the user is able to retrace his steps and develop different design alternatives as required. Connecting the Augmented Urban Model with existing modelling programs would further enhance the workflow.

The designer can profit from simulations as a way of verifying that their underlying rules and parameters are correct (Negroponte, 1970). Analyses and simulations that are applied in urban planning include shadow casting and lighting conditions, access and connection, visual access and visual relationships, climatic and other ecological as well as energy-related criteria. With the aid of the Augmented Urban Model the results of different analyses and simulations can be located within the physical model, facilitating the ability to evaluate the performance of an urban design solution. The Augmented Urban Model also facilitates the use of simulations and analyses, especially in early design stages, as there is no additional effort involved to enter and adjust the model data for various alternative designs. It is in early design phases that the results of analyses can have the greatest impact on the future performance of an urban design solution.

The urban planning process is an intense communicative activity, as it requires cooperation between all the people involved, including the design team, its partners and important decision makers, and not least the community itself. The Augmented Urban Model's simple mode of interaction as well as its way of displaying abstract information physically means that it helps the layman understand complex urban problems more readily. As a result, it can be used to support dialogue between various stakeholders and also help to facilitate participation in the planning process.

The Augmented Urban Model can also support cooperation and communication on a smaller scale, e.g. among the members of the design team. It can help evaluate and analyse design solutions using its computer-aided tools and as a result supports design and performance decisions. Furthermore its input devices are spatially distributed, i.e. there is no so-called 'gate keeper' who controls and executes inputs and changes to the display of information as it would be the case with conventional input devices such as the mouse and keyboard. This means that changes can be performed collectively. Each team member can participate in finding and optimizing a solution by manipulating model elements and selecting criteria (Maquil et al, 2008).

5. Conclusion

As discussed in this paper, physical and digital models fulfil different functions and tasks in architectural and urban design planning processes. Whereas physical models are primarily used as design tools and to represent and communicate a design, digital models are employed beyond that for performance analysis and to facilitate planning.

The great advantage of physical models is their physical and spatial presence, which communicate an immediate idea of three-dimensional design concepts. The physical representation of building blocks makes it possible to assess and experience space in a way that up to now could not be achieved by virtual means. Unlike two-dimensional digital or analogue representations, the physical model is directly assessable and manipulable. It can be experienced with all the senses. The advantages of the digital model are the flexibility of its data structure which can be stored, processed and distributed, and the ability they afford to perform dynamic analyses and simulations that help to improve the performance of a design solution. Digital models offer structural and functional facilities that static, physical models do not possess.

In current architectural and urban design processes, physical and digital models are used according to their respective specific characteristics and qualities, the disadvantage being that the work process has to switch back and forth between the unconnected analogue and digital models. The TUI-based concept of the Augmented Urban Model, as described in chapter 4, aims to resolve this interruption of the workflow by facilitating a dynamic transition between physical and digital worlds. Using readily available consumer electronics, we have realised this setup as a prototype application.

In general TUIs offer a new kind of user experience for interacting with digital data which is context-related and corresponds to the individual characteristics of the problem. TUIs bring back and reinterpret the tangible qualities of working methods, an aspect that is lost when working with a GUI, mouse and keyboard.

The Augmented Urban Model facilitates the physical and spatial evaluation of the design solution and supports the integration of analyses and simulations in the early design phases. Interaction with the Augmented Urban Model builds on interaction principles that are familiar from interacting with the elements of physical models. As a result, the Augmented Urban Model supports architects and planners in various phases of the design process, and also makes it easier to communicate with laymen, as it is easy to understand and operate.

To conclude, TUIs, such as the Augmented Urban Model, can help to connect together the hitherto independent realms of analogue-physical processes and digital processes. In fields such as architecture and urban design that have a long tradition of working and designing with physical models, these kinds of TUIs can enhance the workflow and help bring computer-aided tools back into a spatial physical context.

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CRITICAL FACTORS AFFECTING THE SUCCESS OF BUILDING INFORMATION MODELING IMPLEMENTATION

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ABSTRACT: *Building Information Modeling (BIM) has drawn much attention from both practitioners and researchers in the Architectural, Engineering and Construction (AEC) industry. As the industry adopts BIM, many have struggled on their way to BIM implementation; however, some found their way in the chaos. As a result, many BIM implementation guidelines have been released by government sectors and private organizations to facilitate BIM implementation. Unfortunately, these guidelines were mostly developed based on clients' perspective and needs. For designers and decision makers of design firms, there are few appropriate references. As practitioners in the AEC industry, based on our experience and observation we identify two categories of critical factors affecting the success of BIM implementation, namely, engineering related and non-engineering related. Successful BIM implementation requires changes in software, hardware and mindset but only the first two are frequently mentioned. In fact, we believe non-engineering factors also play an important role in BIM implementation because in order to realize full benefits of BIM, projects have to be executed in a BIM way, that is, workflow and procedures have to be modified accordingly. Especially in well-structured organizations, initiating such changes requires much time and effort and decision makers may face strong resistance. This paper is developed to provide a heads-up for decision makers reminding them what areas should be well taken care of during BIM implementation. We also indicate that different organizations benefit from BIM implementation differently so decision makers have references on their return on investment (ROI). The three identified engineering factors are (1) goal of modeling, (2) interoperability and (3) area of expertise and the six identified non-engineering factors are (1) industry nature, (2) regulations/contract, (3) business model/project delivery method, (4) organization/workflow, (5) roles in project and (6) team deployment. Problematic scenarios associated with factors are illustrated and discussed.*

KEYWORDS: *Building Information Modeling (BIM), Organization Structure, Industry Nature, Interoperability*

1. The BIM Concept and Practical Problems

The AEC industry, by its project-based nature, is fragmented and a large number of interfaces between software and stakeholders exist in almost every project. Clear and instant communication is the cornerstone for projects in the AEC industry to be executed effectively and BIM serves as a good conduit in the processes involved. With better communication and visualization mechanisms such as four-dimension (4D) simulation, the amount of rework becomes smaller. The integrated processes involved in BIM also connect data in the lifecycle of project delivery, so engineers in downstream can take advantage of their predecessor and avoid reinventing the wheel. As a result, Building Information Modeling has drawn widespread attention from researchers and practitioners in the AEC industry as well as the Information Technology (IT) industry due to its well-recognized benefits from such integrated processes. A major change from traditional 2D drafting to 3D drafting and to BIM design in the AEC industry is on its way.

Along with the development of BIM in the AEC industry, a large amount of BIM-related software has been introduced to the market to facilitate BIM implementation. Many companies in the AEC industry have found their masters or champions in using different BIM tools. Some claim that being able to master a piece or several pieces of BIM-related software equals the success of BIM implementation. However, even mastering several pieces of software is just the tip of the iceberg in the realm of BIM. The concept of BIM needs to be refined; otherwise, the productivity in the AEC industry will show nearly no improvement in the future, a similar trend from 1964 to 2004 shown by the Center for Integrated Facility Engineering (CIFE) at Stanford University (Teicholz, 2004).

Building Information Modeling, if indeed achieved, is a set of iterative processes composed of multiple designs and construction activities performed by different entities. Currently many software packages have the ability to develop parametric models with necessary data, properties and dependencies. If a project can be carried out by a single engineer, there seem to be few issues associated with it, except technical ones that can be easily solved; however, projects in the AEC industry, by their nature, are always combinations of multiple input and these combinations are heavily influenced by both engineering related factors and non-engineering related factors. Both types of factors play key a role in project delivery, the success of BIM implementation and, of course ROI. If these factors are not seriously taken into account when evaluating the implementation of BIM, benefits of BIM will be difficult to harness. There are published BIM implementation guidelines such as the "BIM Project Execution Planning Guide" by Penn State University and the "BIM Handbook" by Eastman et al. (2008); however, many of these are developed from clients' perspectives or focus on a particular country. This paper is developed based on observation of practitioners in the AEC industry, rigorous research in scholarly papers and industry reports to present the following critical factors affecting the success of BIM implementation in a global sense. Exemplary issues associated with engineering or non-engineering related factors that affect the success of BIM implementation are presented in the following sections.

2. Literature review

In 2007, the Center for Integrated Facility Engineering (CIFE) at Stanford University conducted an industry-wide survey on the use and value of Virtual Design Construction (VDC) and BIM in the U.S. (Gilligan and Kunz, 2007) and this study identified and confirmed the benefits and value of BIM. With BIM, projects teams deliver clearer communication, better designs, more accurate estimate, and certain add-on values such as optimizing designs through energy consumption analyses (Chou and Hsieh, 2009). As the trend of adopting BIM and implementing it into practice becomes clearer and has gained much momentum, some organization including government agencies, non-profit organizations, educational institutions and military units have published their own BIM guidelines. These guidelines were all developed and tailored to satisfy the need of associated organizations, mostly clients.

For example, the American Institute of Architects (AIA) developed "AIA Document E202™ – 2008"to define the scope of work in which BIM is involved (AIA, 2008); the Associated General Contractors of America (AGC) also helped to develop a document called "ConsensusDOCS 301 BIM Addendum" for similar purposes (ConsensusDOCS, 2008); the Pennsylvania State University developed its "BIM Execution Planning Guide (the Pennsylvania State University, 2010)"; the State of Wisconsin developed its "BIM guidelines and Standards for Architects and Engineers (the State of Wisconsin, 2009)"; U.S. General Services Administration developed its "GSA BIM guide (GSA, 2007)"; National Institute of Building Sciences (NIBS) developed the “U.S. National BIM Standard (NIBS, 2007)”; Indiana University developed its “BIM Guidelines and Standards for Architects, Engineers and Contractors (Indiana University, 2009)”; and U.S. Army Corp of Engineers developed its “USACE BIM Project Execution Plan (USACE PxP) (USACE, 2010).” The above mentioned documents are examples of BIM guidelines and most of them were developed to smooth project delivery processes and save hassles for clients. Goals and deliverables of projects are identified in these guidelines so that architects and engineers have few problems regarding “what to do.” However, “how to do” or “how to implement BIM into design or engineering firms” is rarely presented. The lack of relevant guidelines may be due to the fact that those are how advanced firms maintain their competitive advantage and how they harness benefits from larger profit margin from being leaders in the industry. Simply put, those are their know-how. In 2011, NBS’ BIM report also pointed out withholding such information is how firms exert business pressure over their competitors. We believe that guidelines teaching firms how to develop their BIM best practices do exist but they, or at least the heart of them, are only available to internal employees.

Implementing BIM into practice requires much larger initial investment from design firms than clients. Many design-authoring tools have other free or relatively inexpensive versions that do not have capabilities in design but allow clients to review deliverables freely. On the other side, designers have to place much larger investment for software, hardware, training, and sometimes organization restructuring. Although the benefits of BIM are clear once BIM is part of firms’ daily work, firms have to survive the initial exploring and chaotic phase to harvest them; otherwise, Building Information Modeling is just another delicate and expensive Fabergé egg. Recently, National Building Specification surveyed the development and adoption of BIM in the U.K. (NBS, 2011) and the report showed that more than two-thirds of U.K. firms were either not using or not aware of BIM. Moreover, the report indicated that many firms that are using BIM tools do not adopt BIM processes. Some consider BIM as simply 3D designs, a more advanced practice than 2D designs. A clear understanding of BIM for all involved stakeholders is necessary.

Table 1: Exemplary Building Information Modeling documents

Name	Nature	Author
AIA Document E202TM – 2008	Contract document	the American Institute of Architects
ConsensusDOCS 301 BIM Addendum	Contract document	ConsensusDOCS (mainly drafted by the Associated General Contractors of America)
BIM Execution Planning Guide	Implementation guide	the Pennsylvania State University
BIM guidelines and Standards for Architects and Engineers	Implementation guide	the State of Wisconsin
GSA BIM guide	Implementation guide	U.S. General Services Administration
U.S. National BIM Standard	Standard	National Institute of Building Sciences
BIM Guidelines and Standards for Architects, Engineers and Contractors	Implementation guide/ Standard	Indiana University
USACE BIM Project Execution Plan (USACE PxP)	Implementation guide	U.S. Army Corp of Engineers

3. Engineering Related Factors

As practitioners, from our daily work and observation, we have identified the following three engineering related factors that have significant impact on the success of BIM implementation: goal of modeling, interoperability and area of expertise. Problematic scenarios are illustrated below for each factor.

3.1 Goal of modeling

Many BIM tools offer great modeling capabilities with high level of complexity; however, sometimes such level of complexity is not well supported by available computing power (Khemlani, 2010). Maximum investment in hardware and software is costly and unnecessary. Although BIM models can store a large amount of data as advertised in commercials, a crude model may be practically sufficient. For example, a fully loaded and detailed BIM model may be necessary if the model will be used during the entire lifecycle of a project including operation and maintenance, whereas a simplified BIM model with limited element properties information may be sufficient for clash detection purposes. The users should appropriately deploy their hardware devices based on the computing power needed.

Also, it is imperative to identify the goal of modeling before a project starts. Three-dimension models do not equal BIM and BIM models should not be treated as end products. The biggest advantage and the goal of BIM are in collaboration and coordination where relevant inputs intersect and decisions are made in a timely manner. Software venders may convince designers of adopting their BIM solutions by showing them how necessary two-dimension (2D) documents are generated automatically from a complete BIM model and any changes made in the BIM model can generate the most up-to-date 2D documents whenever necessary. Such BIM adopters identify being able to generate 2D documents automatically as their primary reason to implement BIM because they appreciate the time savings provided and then they start their BIM processes by designing in a 2D environment and later build their BIM model based on these 2D designs. Such BIM adopters use BIM for the wrong reason because generating 2D documents automatically is just the byproduct of BIM, not the essence of it. Also, they take on the most time consuming aspect of BIM by converting 2D designs to a 3D environment. In this case, they only use BIM tools for drafting instead of design, which lost the center of BIM concept. Designers still exchange ideas in a 2D environment and conflicts are resolved in the same environment, too. Moreover, such process is redundant because the same design are drafted twice, one in 2D and the other in 3D.

3.2 Interoperability

A large number of interactions among different entities exist in every project and, as a result, interfaces for these interactions are crucial for smooth project execution and delivery. The number of interoperability issues increases along with the increase in number of available BIM tools because most commercialized BIM tools are developed with proprietary file formats or information. Information may be interpreted in wrong ways or fail to be interpreted by non-authoring tools. The formation of Industry Foundation Classes (IFC) was to resolve these issues but some still exist (Chou and Hsieh, 2009). The most widely used IFC is IFC 2x3 and many software venders including Autodesk, Bentley, Gehry Technologies, Graphisoft, Nemetschek, Solibri and Tekla support this file format (Khemlani, 2010). However, in most authoring tools, designs are still stored in their native formats and then are exported as IFC files. Certain information is still lost after files are saved in the IFC format instead native formats. For example, designers may specify certain properties or information of an element in authoring tools, but if IFC does not have a corresponding place to store that properties or information, they are usually lost or misplaced when files are saved in the IFC format. We tested that even if an IFC file is opened by its authoring tool, say Autodesk Revit Architecture, which generates the IFC file, some missing properties cannot be retrieved.

Besides IFC, some software venders have also reached agreements on developing other interoperable file formats for file exchange by sharing certain proprietary information. After Autodesk and Bentley have reached such agreement to solve interoperability issues, i-model is formed. A plug-in developed by Bentley can be mounted on certain Autodesk software and designs developed in software such as Autodesk Revit Architecture can be exported as i-models with the file extension ".i.dgn" that can be read directly by certain Bentley software such as Bentley Navigator and Bentley MicroStation. However, i-models were designed for design review, coordination and collaboration purposes so users have limited capabilities in editing them.

Given the fact that no perfect solution solving interoperability issues is available, clients, designers and all other stakeholders should identify interoperability issues when selecting their BIM tools. If only one tool is used, there exist few issues but stakeholders should remember their capabilities to review, edit and review designs are limited to what that tool offers. If a small number of tools are used, stakeholders can only focus on making sure the links between different tools are sound. If stakeholders decide to take full advantage of a spectrum of tools, they should be aware of potential interoperability issues involved.

In fact, interoperability issues come from interoperability requirement so stakeholders should know their interoperability requirement up front. That way they can look for appropriate solutions. In many cases, losing certain information during file exchange may be acceptable.

3.3 Area of expertise

Building Information Modeling is not simply objects modeling or design automation; in fact, it requires input from both engineers/designers and IT professionals. As people are trying to make sense of what BIM really is, professionals from both sides rush to this newly developed area. In some organizations, Building Information Modeling collaboration is led by IT professionals whereas in others, it is led by engineers or designers. However, neither engineers/designers nor IT professionals alone can make BIM a reality. For example, engineers or designers who understand the flow of projects well have relatively weak skills in customizing their workspace or reports. Although they possess design fundamentals, they still need external input from IT professionals. Information technology professionals, on the other hand, who lack of relevant engineering knowledge and clear understanding of project workflow, are good at providing the above mentioned support. However, IT professionals may come up with workflow or designs considered impractical or inappropriate by engineers or designers. After all, engineering and design is still the center of BIM, a tool that was developed to help engineers and designers to achieve better productivity in their work and workflow, so we believe that BIM collaboration should be led by engineers or designers. In such collaboration, engineers or designers should work closely with IT professionals to harness the most from their support.

4. Non-engineering Related Factors

In addition to engineering related factors, we also found several other factors that are crucial to companies' strategic planning on BIM implementation. Some of these factors are frequently mentioned and studied as engineering related factors are by researchers and practitioners; however, some of them such as industry nature require further investigation.

4.1 Industry nature

Aside from the common fact that projects in the AEC industry are project-based in nature, the AEC industry varies greatly from one country to another. Understanding differences in industry nature and assumptions becomes increasingly important as boundaries between countries blur due to technology advances. Moreover, given that companies sometimes collaborate with foreign partners through Joint-Venture or other forms, understanding partners' background smoothes their collaboration. Therefore, for practitioners it is imperative to know if the desired BIM tools are developed with the same assumption embraced by them.

For example, in certain countries, engineering designs are performed by general contractors directly whereas in other countries, general contractors are not responsible for such work. Also, certain professions such as drafting may not even exist in some organizations because engineers or architects in those organizations are responsible for both engineering/architectural design and drafting. For those engineers and architects, because they have experience in drafting and currently many BIM tools offer intuitive and user-friendly user interface, BIM can be easily implemented in their work; however, for engineers who do few drafting work, they may struggle on their way to BIM because aside from engineering design, they have to learn drafting. Although the entry barrier to drafting is lowered by user-friendly interfaces of BIM tools, decision makers should evaluate how well their engineers can learn new BIM tools.

4.2 Regulations/Contract

Having relevant regulations in place is a critical element for successful BIM implementation. Still, most of designs are signed off by designers or engineers on paper today. How to sign off BIM models or how to make sure if documents being signed off are generated from BIM models and contains all relevant information deserves serious attention. Moreover, since it is difficult for clients to scrutinize BIM models delivered by contractors in a timely manner, how to configure contracts for BIM projects is worth more research. At the time of writing, there is no prevalent regulation that provides guidelines for the above topics. All stakeholders involved in projects should keep their close eye on future regulatory development.

In practice, deliverables in BIM projects are sometimes not defined clearly. In all cases, an end BIM model or several BIM models are to be delivered to clients. However, what information is to be stored in BIM models remains unclear in many cases. Objects in BIM models have more information such as properties, relationship to other objects, etc., than simply the associated geometry. Also, because BIM models are sometimes composed of many referenced files, engineers and designers should understand if their clients want a single composite file or a master file with many referenced files. They should always keep in mind what is required in their deliverables since building a modeling with geometry only requires much less work than a model with fully loaded information. They should consult their clients if model requirement is not stated in the contract. Not only does clarifying model requirement avoid unnecessary work or failing to meet clients' expectation, but it avoids future argument over such matter.

Additionally, ownership, authorship, or copyright of BIM models are other rising issues since ideally BIM models are developed incrementally along the lifecycle of a project. Project members all contribute to the end models delivered to clients but it's hard and maybe unnecessary to claim that certain portion of the deliverables belongs to specific contributors. Since most BIM projects states that BIM models are to be handed over to clients at the time of completion for future maintenance and reference, contributors of BIM models basically lose their ownership, copyright or authorship of their parts of contribution if they want to participate in BIM projects. However, many engineers and designers still hesitate to give models with complete property and information to their clients because they believe those models contains their know-how or proprietary information. Given that the trend of handing over BIM models at the time of completion is embraced by most clients, engineers and designers may alternatively ask their clients what information and properties are to be delivered and negotiate model requirement in contractual terms with them based on clients' answer. For example, not all clients need parametric models. If they only use models for operation and maintenance purposes, geometry and associated properties indicating manufacturers and maintenance record may be sufficient. Engineers and designers can deliver appropriate models accordingly.

4.3 Business model/Project delivery method

Businesses achieve different levels of ROI from its BIM implementation and business models play important roles in determining the outcome. The iterative nature of BIM fits different business models such as Design-Bid-Build (DBB), Design-Build (DB), Turn-Key, Integrated Project Delivery (IPD) and Design-Assist differently. Generally speaking, projects with integrated workflow or teams who work collaboratively can achieve more benefits from BIM implementation (Eastman et al., 2008). Decision makers should bear in mind that only partial benefits from BIM may be achieved if BIM is not implemented throughout the entire project. This factor is especially crucial to firms that provide specialized expertise such as structural design instead of others who provide total solutions because total solution providers have better control over the entire process whereas firms with specialized expertise usually take part of only a specific section of the entire process and are thus limited by upstream and downstream players.

4.4 Organization structure/Workflow

"*Adopting BIM is not just a matter of buying and using some software* (NBS, 2011)," and successful BIM implementation requires appropriate organization structure (Levitt et al., 1994). With BIM, bureaucratic processes can result in even larger impact on its productivity than without BIM. Also, certain professions such as drafting may gradually disappear.

Building Information Modeling changes workflow in the AEC industry. As indicated by the survey conducted by NBS' BIM report (2011), "*adopting BIM would require changes in our workflow, practices and procedures.*" Two-dimension drafting usually works on linear workflow, e.g., work is passed to Engineer B after Engineer A finishes it. With BIM, design integration can be hardly achieved if similar workflow remains unchanged. Applying workflow previously used in 2D environment to BIM projects is like hitching a horse to a car. Although cars are more powerful than horses, being led by horses does not yield any outstanding performance. In fact, the performance of a car which is led by a horse is even worse than a horse alone, because the car has no control over its direction. Similarly, BIM implementation is like a double-edged sword. Implemented in a traditional workflow, decision makers quickly receive complaints that BIM is slower and not cost effective. However, the power of BIM can be unleashed if workflow is modified based on project needs. Moreover, collaborative workflow also requires decision makers and stakeholders' active involvement because many decisions have to be made on the fly to achieve the true time and cost savings.

4.5 Roles in the project

The richness of a BIM model is increased along with its project lifecycle. Practitioners, especially downstream ones, should pay attention to what is provided from the upstream. They should be aware of additional workloads if BIM models provided from the upstream cannot be used. This happens frequently due to interoperability issues. Rebuilding a BIM model from scratch places a huge burden on engineers and designers' shoulders because of extra work and the fact that they may not have relevant professional knowledge in other areas. Engineers and designers can solve this problem by clarifying the work scope with clients up front and reaching an agreement with them on specifically what type, format, extension, etc., of files or models will be provided as the foundation upon which their new work will build.

Moreover, decision makers have to realize that not all benefits of BIM can be achieved, given their work scope, so that they are not overwhelmed by software venders with irrelevant benefits of BIM. For example, general contractors can greatly benefit from 4D simulation because their job is to coordinate subcontractors. They can simulate the flow of onsite vehicles, equipment and personnel up front and modify their plans if necessary. However, for upstream players such as architects or engineers, if scheduling or sequencing is beyond their work scope, simulating construction sequence does not provide many benefits, although showing a short 4D simulation may be good for presentation purposes.

4.6 Team deployment

Different team deployment results in different loads of data exchange. As model size becomes larger, how teams are deployed (co-located within Local Area Networks (LANs) or geographically dispersed using Wide Area Networks (WANs)) has significant impact on data exchange efficiency (Khemlani, 2010). For example, among major BIM tools such as Revit Architecture, Bentley Architecture, ArchiCAD, Allplan Architecture, Vectorworks Architect and Digital Project, Revit Architecture has significant performance issues. This may be due to its file structure and the fact that when files are saved, many other information and properties are saved to the same files. When collaboration resides within LANs, performance issues are less significant; however, for collaboration over WANs, such issues become more problematic. Refreshing or syncing files saved on remote servers over WANs may take a long time due to network capacities and efficiency and productivity are therefore reduced. Some software venders have developed their solutions to help solve such issues. Many of their approaches are based on a concept– refresh or sync only modified, added or deleted parts instead of the entire file. For example, the solution provided by Autodesk is called Revit Server which uses a central server and multiple local servers for each LAN. Initially, engineers and designers work on a copy of central model saved on local servers. As team members work, local servers silently request updated data from the central server if any changes are made by other collaborators so the updates are readily available upon request. Decision makers should remember that one single BIM tool may not satisfy all project needs. A company may in some projects work on collaboration solely within LANs and in other projects perform collaboration over WANs. Using appropriate BIM tools and configuring work environment accordingly for different projects is the key to optimal performance.

5. Conclusion and Suggestions

The benefits of BIM have been widely recognized and promoted by leading practitioners in the AEC industry and software vendors. However meanwhile the word BIM is still considered a buzzword to many. To some, BIM is all about visualization and automatic scheduling; to others, BIM is more complicated and it includes processes and procedures. Many times too many features are packaged into BIM but in fact, they have little to do it. The benefits of BIM are harnessed through its integrated processes. A common misunderstanding about BIM is that producing 4D simulation videos is BIM. However, after producing videos, many start to question what they can do with these videos. Going back to the origin of BIM, we can see that simulation is just a interim product of the integrated processes, not the benefits. The real benefits emerge here because when input from engineering designs and scheduling come together, logistic issues can be resolved up front to avoid delays. Building Information Modeling should only be implemented after decision makers realized what BIM is and evaluate what efforts such as time, money, training, changes in process, etc., are necessary to take to configure each of the above mentioned factors appropriately to build a BIM-friendly environment. We believe, as the industry progresses, that BIM will be defined more and more clearly but before seeing a well-defined BIM, only those who truly understand what BIM is can make use of it and take the lead in the AEC industry.

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INTEGRATION OF BUILDING INFORMATION MODEL WITH BUILDING ENVIRONMENTAL ASSESSMENT TOOLS FOR BUILT ENVIRONMEN

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ABSTRACT: *Buildings consume resources and energy, contribute to pollution of our air, water and soil, impact the health and well-being of populations and constitute an important part of the built environment in which we live. As a result, carbon reduction becomes a global target and a goal has been set by the UK Government to reduce 80% of the carbon emission by the year 2050 below 1990 level. Therefore, the ability to assess our building designs with a view to reduce their impact automatically from their 3D/BIM representations enables design professionals to make informed decisions on the environmental impact of building structures.*
This paper aims to high-light the benefit of the integration of Building Information Model (BIM) with Building Environmental Assessment (BEA) tools to minimize cost (money & time) and environmental impact of the building life cycle, and attempts to encourage the efficient use of energy in order to meet UK government carbon reduction targets, as a crucial function needs to be considered at the outline design process for built environment. One of the research objectives is to develop a design framework and tool for integration of assessment tools and BIM technology in order to fit them in the design and construction process. The result showed that the time taken to enter data into the energy simulation software could be eliminated by integrating BIM technology with energy simulation software tools.

KEYWORDS: *BUILDING INFORMATION MODEL, BUILDING ENVIRONMENTAL ASSESSMENT TOOLS, SUSTAINABLE BUILDING DESIGN*

1. Introduction

In the UK, 40-45% of CO_2 emissions come from energy used in our homes and buildings (UK Green Building Council, 2011). We need to almost completely decarbonizes our built environment by 2050, through a combination of very high energy efficiency of buildings and on-site renewable energy (Carbon Trust, 2010; UK Green Building Council, 2011). In addition, carbon reduction becomes a global target and a goal has been set by the UK Government to reduce 80% of the carbon emission by the year 2050 below 1990 levels, (Defra and Decc, 2009). Therefore, the ability to assess our building designs with a view to reduce their impact automatically from their 3D/BIM representations enables design professionals to make informed decisions on the environmental impact of building structures, (Tucker, et al. 2003). Loots and Irurah, (2005) argued that "if decisions that are made in concept and design stages of projects respond to sustainability objectives and targets, many of the negative outcomes can potentially be prevented, or at least, reduced. However, the absence of tools and mechanisms which systematically link sustainability criteria, targets and assessment outcomes with decision-making processes significantly inhibits the transformation from conventional to sustainability practice in the built environment." To support design decisions at the very early stages of the design process a BIM technology has been adopted which will enable a 'sketch' to be made of building energy performance. This approach is in agreement with many experts (Serra et al. 2000, Baker and Steemers 2000) who recognized that in early design, any calculation method employed must be quick and easy to use in order to allow the designer to explore a number of options. In view of the major gaps identified, sustainability assessment tools need to evolve capabilities in simulation and decision-modelling as well as design generation in order to work towards closing the gaps identified (Loots and Irurah, 2005). Simulation assessment tools, modelling tool and decision support tool need to be adopted and integrated. Therefore The Revit Architecture BIM modelling tool and IES whole building energy simulation software were chosen to pilot the framework. In essence the framework presented aims to integrate existing technologies and sustainable building codes to bridge the gaps in current approaches to sustainable building design for built environment. This includes the integration of;

- Revit Architecture BIM modelling tool.
- Energy simulation tools and approaches for analysis of building energy performance including estimations of the potential of active renewable energy technologies.
- National Calculation Methods (NCM) and codes to support energy efficient and sustainable buildings.
- Multi-Criteria Decision-Making (MCDM) approaches and tools designed to support stakeholder decision making in the building design process.

The framework is developed so that an architect can iteratively re-design a building and immediately see if the air pollutant emissions, energy consumption, or operating costs, have been reduced or increased by different design options. This will ensure that designers, clients and other stakeholders have the relevant information required for an assessment of cost versus environmental impact with regard to different aspects of a building's design. In this way building owners and users will have the opportunity to minimise operating costs and optimise building performance. The remainder of this paper is divided into three sections. The first, discusses the value of BIM in current practice and academia and to identify gaps in current tools and knowledge. The next section then goes on to outline the design framework developed in this research to support the integration of the design methods and tools required for sustainable building design. The third section presents a case study to illustrate how the framework can facilitate the integration of BIM and BEA. The fourth and final section discusses the research findings, draws some conclusions and presents the future work of this research.

2. BIM and BEA in Current Practice and Academia

The advent and proliferation of BIM in the building industry has produced a wealth of information related to its use and implementation. There are numerous case studies (Khanzode et al. 2008; Eastman et al. 2008; Kymmell 2008) that provide anecdotal evidence to support the idea that the use of BIM makes the building process more efficient and effective. IntUBE Project (2008) reported that "Advances in computing technologies are also facilitating improved techniques within the design phase energy profiling facilitated by the use of BIM tools which allow the creation and use of coordinated, internally consistent, computable information about a building project in design and construction." In principal the models developed by BIM could be used to improve the energy efficiency of the built environment by assessing both the predicted energy performance of buildings and methods used in design phase. The value of BIM is also a challenging topic for many in academia. Gilligan and Kunz (2007) focused on the rate of adoption of BIM and of virtual design and construction (VDC) and the effects of that adoption process. InPro project, (2009) reported that "the use of BIM offers the opportunity to support a performance based design where the required data to evaluate the product performance can be imported to different type of analysis software." Dawood et al. (2009) focused on using BIM at the early design stage to design sustainable buildings and the result showed the benefit of using BIM as a platform, coordinating and visualizing tool to make the accurate decisions. According to Krygiel et al. (2008) "The poor interoperability between Building Information Models [BIM] and energy simulation tools also hinders a generalised use of energy analysis at the design phase." Therefore, we need for more progress on integrating BIM with energy simulation tools, as these problems have not been totally resolved in current software.

2.1 Current state of the art tools

2.1.1 Building Environmental Assessment (BEA) Tools and Their Application

Building environmental assessment tool or building energy simulations tool are conducted by design professionals (architects, engineers and energy consultants etc) using building design and energy analysis software tools to analyze the energy performance of their designs. For example, the energy performance feedback provided by whole building energy analysis tools allows designers to assure equipment is properly sized for the design conditions of a given building and that the part-load performance of the building subsystems are optimized to provide a comfortable environment (Jacobs, 2002). A database developed by the U.S. Department of Energy (DoE) currently lists almost four hundred energy tools designed to simulate the energy performance of buildings and/or their components (US Department of Energy 2011). Many of these tools capable of whole building simulation are designed to be used during different phases of the building design lifecycle and have different functionalities, see table 1, which presents a selection of widely used whole building simulation software highlighting the differences in their functionalities.

Table 1: Comparison of the functionality of whole building energy simulation tools

Tool attributes	SBEM	IES-VE v6.1	TAS	Design Builder
Integrated with BIM	N	Y	N	Y
Dynamic simulations	N	Y	Y	Y
Consideration of internal shading	Y	Y	Y	Y
Consideration of external shading	N	Y	Y	Y
Geometry/graphic approach	N	Y	Y	Y
Unlimited orientations	N	Y	Y	Y
Renewable technologies	N	Y	Y	N
Global climate data	N	Y	Y	Y
Calculation of natural ventilation	N	Y	Y	N
Building regulation Part L	Y	Y	Y	Y
Easy to use	N	Y	N	Y
Construction cost	N	Y	N	N

2.1.2 Building information modeling software tools

BIM tools are used to generate graphics and information about building components which demonstrate the entire construction planning, project costing, lifecycle costing, etc (Autodesk, 2003). Ideally the building information models produced by BIM tools would enable users to identify potential problems during early stages of a project; reduce the design errors; save cost and time and accurately predict the energy consumption during the lifecycle of the building. Currently, a number of BIM applications are on the market, provided by a host of different software vendors. The most used architectural software packages which support BIM are Revit, Bentley Architecture, ArchiCAD and Digital Project (Eastman et al. 2008), the following is description of the most popular tools:

Revit: was launched by Autodesk in 2002. It is composed of three modules, Revit Architecture, Revit Structure and Revit MEP (mechanical engineering and plumbing). It includes interfaces for energy simulation and load analysis using the gbXML schema. It has a user-friendly interface and is therefore easier to learn than some of the BIM tools on the market. It has a set of libraries provided by third parties. However, one of Revit's limitations is that it does not support curved and complex geometries, (IntUBE reports, 2008). Revit is the newest and most technologically advanced BIM application. Revit was designed from the ground up as a BIM tool to specifically address problem areas of the architecture, engineering and construction (AEC) industry: communication, coordination and change management. Being able to go direct to fabrication with the designs, provide digital shop drawing submittals and execute 4D construction planning and for greener designs and energy analysis are just a few of the possibilities. Revit is a technological platform that supports architectural, structural and mechanical disciplines. It's supported by a patented parametric change engine that is unmatched in sophistication. It's also the leading software package in the international market. It's not the only package out there, but it offers the most holistic approach, (Krygiel, et al. 2008). The Revit parametric building modeler represents the building as an integrated database of coordinated information.

Bentley Architecture: Bentley Architecture, produced by Bentley Systems, is a descendent of an earlier BIM tool called Triforma. It integrates applications for structures, mechanical systems, electrical systems, facilities management, and site planning. Unlike Revit it supports complex, curved geometries. However, its interface is not user friendly and it is therefore hard to learn and navigate.

ArchiCAD: is the oldest BIM tool on the market. It was first promoted in 1980s by Graphisoft, but was subsequently bought by Nemetschek. It has interfaces for energy analysis and other sustainability functions supported by gbXML, Ecotect, Energy+, ARCHiPHISIK and RIUSKA. It has an intuitive interface and is therefore relatively simple to use. However, its updating rules for parametric objects are limited.

2.2 Integrating of BIM with building environmental assessment tool

The general problem addressed in this research is the integration of building simulation tools and building design to predict the building performance and to generate data. The focuses on utilizing BIM for Built Environment in current practice, many other building models do not contain sufficient information for building performance analysis and evaluation. BIM has the potential to change the role of drawings for the construction process, improve architectural productivity, and make it easier to consider and evaluate design alternatives. BIM will also aid in the process of integrating the various design teams' work, furthering encouraging and demanding an integrated team process, (WBDG, 2010).

At the early design stages, the building design is a rough form without much detailed information which makes it difficult the use of simulation engines. Rather than complex simulation programs that require large amounts of data from the building design, what is needed at this conceptual stage are simple tools that enable designers to explore different solutions having quick and easy results to evaluate and compare them. Nowadays, most of simple simulation engines have two main shortcomings: they usually cannot simulate complex passive strategies and they not include a global energy balance or systems (Crosbie et al. 2010a). At this stage of the design and construction process the information available for energy simulations is limited. Therefore to support design decisions at the very early stages of the design process a BIM technology has been adopted which will enable a 'sketch' to be made of building energy performance. Therefore, we propose to combine simple simulation models with summarized information available in the BIM model and simulation tools for improving the energy efficiency at the concept stage for Built Environment. However, as noted by Karola el at.(2002) the level of integration between BIM and BEA tools does not fully eliminate the problems as there are many corrections necessary after data is imported to BEA tool from BIM tool. This problem has been narrowed down to computational support for different types of building design. A new design framework has been developed in this research to play as a process for the integration and decision helper.

3. A New Design Framework

During stage C of the 'RIBA Work Stages' a full set of tendering documentation including design brief, site data, project schedule, project budget and client requirements are prepared and given to tendering contractors/architects to prepare the full design proposal. Following stage C in stage D of the 'RIBA Work Stages', investment decisions are finalised and applications for planning permission are made. The framework presented here suggests a method for breaking down stage C into 6 sub stages which incorporate processes that enable issues of building sustainability to be addressed when the opportunity is still open to change the design variables which have the largest impact on the energy performance of a building is still open. Accordingly, stage C divided in to three main parts, first part is modelling [part C1], second part is data generation and simulation [part C2] and third one is decision support [partC3].

The initial input into stage C is the conceptual/outline design proposals developed in stages A and B. It is suggested here that different design alternatives are developed by - using BIM technology - which meet the clients brief based on the outline designs in stage C1.1. These alternative designs, where possible should include different options for building orientation, shape, wall-window ratio and passive renewable energy technologies (such as buffer zone, solar walls, etc.) as these have the largest impact on the energy performance of buildings. Following this an assessment is conducted in what we have called stage C2.2, to assess the viability of different active renewable energy systems for the alternative building designs identified in stage C1.1. Following this an building environmental assessment tool (BEA) is used to assess the energy costs, heat gain / loss, and CO_2 emissions of each of the design options developed in stage C1.1 in stage C2.3, the full integration of BIM with BEA need to be achieved.

National Calculation Methods (NCM) such as SAP for dwellings and SBEM for non dwellings are used to calculate target emission rate (TER) and building emission rate (BER) in stage C2.4. The data generated from key stage C2.2, C2.3 and C2.4 is used as an input for stage C3.5 the outputs of the design assessments are checked against the relevant benchmarks and current regulation. Potential of sustainability standards code such as Sustainable Homes (CSH) or BREEAM rate is also indicted in this stage in order to achieve better rate in future. In the next stage (stage C3.6) Multi-Criteria-decision-Making (MCDM) is used to help clients and/or other stakeholders select the optimum design which most closely fits their requirements. The optimum building design is used to inform the next stage of design and construction process which is key stage D. To help the design team and the client for making a decision in stage C3.5 and C3.6 a decision support tool called Sustainable Design Optimisation Tool (SDOT) has been developed and integrated with the design framework as one of the research objectives (see figure 1).

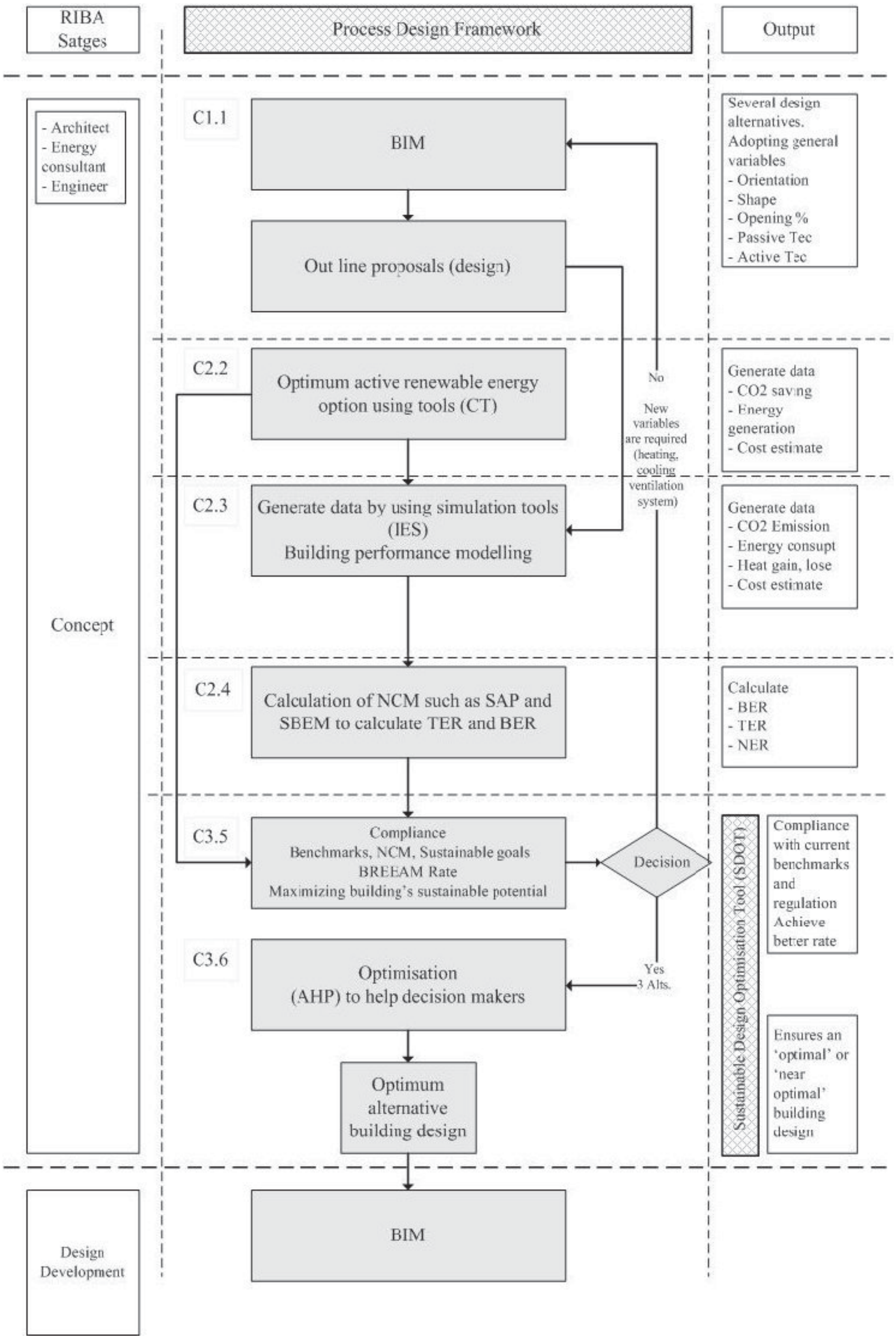

Fig. 1: Detailed design process framework for RIBA stage C

The core of the design framework and the integration of the system, is illustrate in figure (2) this diagram is useful to understand how the system components are integrated to relate the involved processes, inputs and the outputs. The diagram is another way to represent the conceptual process.

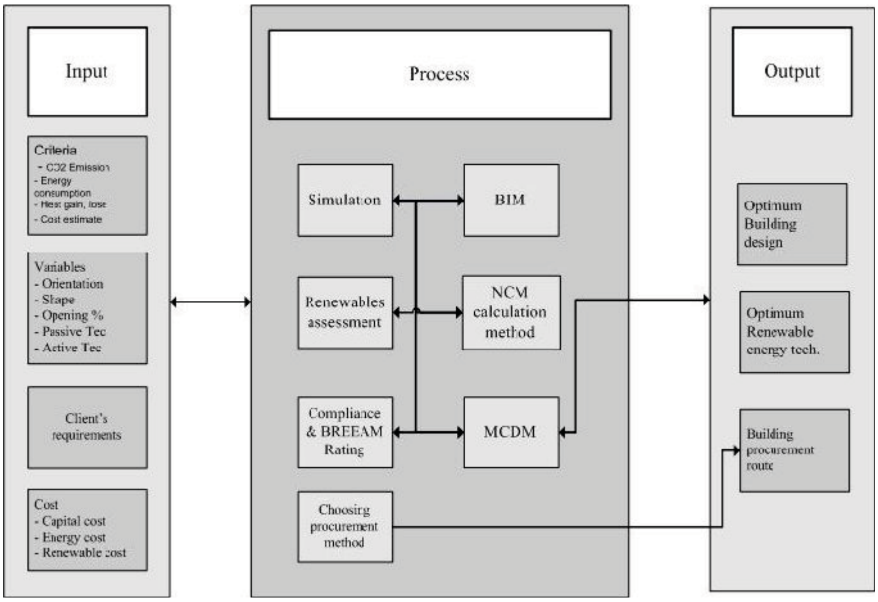

Fig. 2: Shows the core of process integration

4. Case Study

In order to discuss and demonstrate the framework a case study has been developed using a primary school in Durham County. In this case study we had replicated a possible design process using the example of a school for 105 pupils with a real data and take all the client requirements and needs in to consideration in order to make this case study more realistic. Alternative building designs have been modeled. An energy simulation was carried out for these alternatives. The Revit Architecture BIM modelling tool and IES whole building energy simulation software were chosen to pilot the framework (see figure 3). Results for three alternative building designs (consisting of results for building CO_2 emission, energy consumption, renewable energy potential, capital cost, and occupier-comfort) were generated and they were used as an input to another stage throughout the process (Crosbie, et al. 2010b). The output from the design framework is an optimum building design that has passed current regulations and benchmarks, and obtained maximum BREEAM credit at the outline design stage in order to maximize a build's sustainable potential. This approach allows stakeholders to evaluate and choose amongst alternatives based on multiple criteria using a systematic analysis that overcomes the limitation of unstructured individual or group decision-making (Keller et al. 1999). The case study presented illustrates that current tools and methods can be integrated to support consideration of the energy performance of a building design when the opportunity to substantially improve the energy performance of that design is still open. The case study demonstrated the facilitation of the integration of BIM and BEA

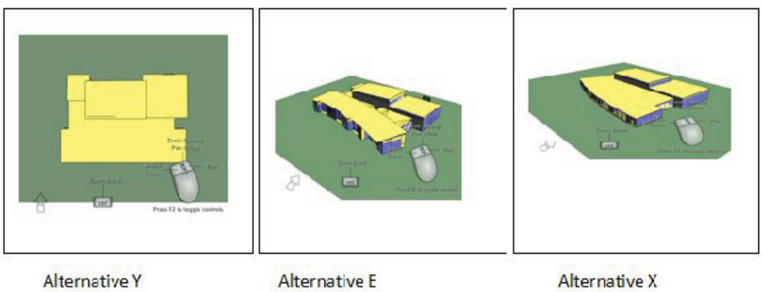

Fig. 3: Design alternatives

5. Conclusion

The recognition of the need for carbon reduction from the built environment, along with UK directives, more stringent building regulations and general environmental concerns has lead a number of researchers to develop general lifecycle design frameworks for buildings to support energy efficient building design. This paper has argued that there is a pressing need for the integration of the methods and tools to support sustainable design with BIM technology. This mixes together analytical, technical and applied skills and involves linking a range of technologies. The research presented provides practical guidance to design professional on how and when to use building energy simulation tools and BIM technology to support environmentally sound design practices. This is achieved by developing the framework for the integration and identifying and filling some of the gaps in current tools. However further research is required to support the use of these approaches by architectural professionals working in the construction industry. This could take the form of Knowledge Transfer Partnerships or integrated research projects which are conducted in conjunction with architectural and construction professionals. Ideally the next step in the research presented in this paper is to care several semi-structured interviews with professional people working in this field to make sure that the process been followed and the decision support tool (SDOT) has a reality check, and to take their opinion into consideration now and in the future to improve the research findings.

To conclude the overall advantages of this study, clients need efficient designs and buildings that could be delivered by adopting the research framework and tool to get more for less; lower analysis cost/time and cost/time effective, higher value; comparison of different alternatives; achieve sustainable community and make the analysis more accurately. The result showed that the time taken to enter data into the energy simulation software could be eliminated by integrating BIM technology with energy simulation software.

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LINKING PRODUCT AND PROCESS DATA IN THE MODELING ENVIRONMENT 'CISMO'

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ABSTRACT: *This paper presents the process model used in the modeling environment CiSmo (CAD-integrated simulation modeling for the simulation of construction processes). CiSmo was implemented in the course of a research project supported by the German Research Foundation (DFG). It is a modeling environment for the creation of agent-based simulation models for the simulation of construction processes. Further, CiSmo can either automatically create construction schedules from CAD-drawings or on the basis of simulation results, which facilitates simulation-guided resource planning. This supports the decision making in the phase of the preparation and execution of construction work. CiSmo is integrated in the CAD environment AutoCAD Architecture. It uses 3-dimensional building models (product model) and additional process data to create the simulation model(s). The product model contains general information like geometry or quantity data for the simulation. The connection of these data with the simulation reduces the effort for generating the simulation model. The process model in CiSmo describes the building construction methods. Further, it describes the activities and dependencies in the construction process. The model enables the definition of resources (labor force, machines and material). CiSmo also has a data base. The majority of the process data are saved in this data base, so that these data can be reused in future projects. This paper focuses on the description of the link between the process and the product data in CiSmo.*

KEYWORDS: *product data, process data, simulation in construction, agent-based simulation, CAD-integrated simulation modeling.*

1. Motivation and Research Objectives

It can be a challenge in many large construction projects to keep an overview of the time scheduling. It is often difficult to determine the dependencies between the involved trades, for example, which can easily lead to mistakes. We suppose that the use of simulation in construction sequencing can help to overcome such challenges.

In the Department of Construction Management at the University of Kassel, we conducted a survey among professionals working in architectural and engineering offices in Germany to explore problem areas in practice (Franz and Kordi 2010). In total, around 150 professionals participated in the survey. In the following, some questions and answers of this survey are presented:

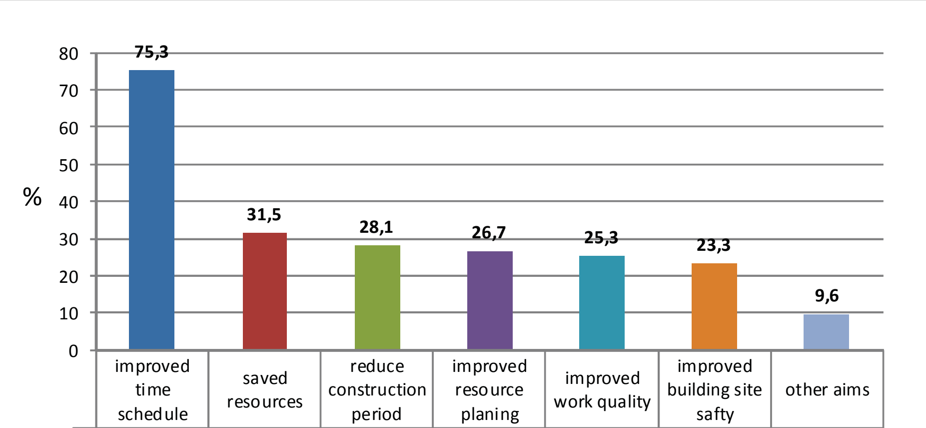
Question 1: How high do you think is the effort of generating detailed time schedules, and which problems are likely to occur?

Answer 1: 64% of the respondents said that the effort is high. They see challenges in considering dependencies between the involved trades in a project, and keeping the overview when dealing with large plans. Further, they stated that the effort of keeping the plans up-to-date can be very high.

Question 2: Would you use our simulation system to facilitate the planning of the construction process?

Answer 2: 80% of the respondents said that they would use the system, if it helps to generate economical or organizational advantages.

The results for question 3 (What would you expected from in a relevant simulation system?) are shown in the following bar chart:



%	improved time schedule	saved resources	reduce construction period	improved resource planing	improved work quality	improved building site safty	other aims
%	75,3	31,5	28,1	26,7	25,3	23,3	9,6

Fig. 1: Expectations of the respondents from the simulation system (Question 3)

Our survey confirmed our 'theory' that there are challenges with time scheduling of construction projects in practice, and that these challenges can be met by using a simulation system.

In contrast to other industries, simulation in construction has had no great significance so far. Since construction projects are unique, simulation models require great efforts concerning data acquisition. The data has to be collected 'manually' for every single project. This requires time resources which are not available for most construction projects. If time can be spared for data acquisition, lack of experience in collecting data and modeling can still result in useless or incorrect simulation models.

We state that a system is needed to support the data acquisition and modeling process, so that simulation in construction can be established with less effort.

A complete description of the construction process in a simulation model requires the following data:

- product data (i.e. the CAD-model of the building, containing quantity and coordinates of the components)
- process data (i.e. a description of the construction methods and activities)

- resource data (i.e. labor force, machines and material)
- description of the production environment (i.e. the building site facilities and the construction sections)

We developed the modeling environment CiSmo (CAD-integrated simulation modeling for the simulation of construction processes) to set up the above mentioned data, so that they can be reused and linked with each other. CiSmo was created in the course of a DFG (German Research Foundation) research project at our institute. It is integrated into the CAD-environment AutoCAD Architecture from Autodesk.

CiSmo enables the user to define all necessary resources and processes needed for simulation. The user draws the construction sections and the building site facilities into the CAD-model, which enables CiSmo to generate agent-based simulation models by combining the resources and the process data with the CAD-model and the building site facilities (Kugler and Franz 2010). In addition, CiSmo can automatically generate schedules for the construction sequence based on the same data.

This paper explains how CiSmo links product and process data.

2. Related Works

2.1 Building Product Model

In construction engineering, a building is regarded as a product. 'Product model' then means to save all relevant data of a building in a neutral environment. The data are structurally saved, so that they can easily be retrieved. Besides geometrical data, data about quantities and material costs are saved. Major aim of the 'product model' is the development of a computer model to facilitate and automatize data transfer between different parties involved in a construction project as well as between different software's. The model is not limited to a narrow scope of application. In fact, it covers the entire life-cycle of the 'product', i.e. a building. (Björk 1999) (Hörenbaum 2002). Moreover, the connection between the 3D product model with time schedule results in a 4D model. The 4D model assists with the query for an economical time schedule.

During the last years the term 'Building Information Model' was often used to describe a building product model, particularly by the creators of the CAD-Software.

2.2 Construction Process Model

The Construction Process Modeling describes all processes to generate a building. The process modeling is used in the simulation to support the construction scheduling. One of the first relevant research projects in this field was conducted by Aalami, Levitt and Fischer in 1998. The authors created a formalization of planning knowledge in the form of a computer-interpretable construction method model template (CMMT). In this template every activity is defined as a ‹CAR› tuple, in which C stands for component, A for action and R for resource. Every ‹CAR› tuple is associated with activity elaboration ‹E› and sequencing ‹S› knowledge. With the ‹CARSE› tuple it is possible to generate appropriate activities for each building component in a product model, to link component, action and resource information. (Aalami et al. 1998).

Current research projects focus on the development of process templates to describe frequently used construction processes. These templates are linked to a building model. Based on the link the specific processes of the construction project can then be instantiated. Huhnt and Richter (2010), for example, use project independent sub-process templates, which are related to the components of a building model. The sub-processes of the construction of each component are created based on an associated template. The sub-process templates have activity- and status-templates to describe the relationship between the processes. These templates also contain relationships between the activities and the states. A state of a component is defined as a prerequisite for the activity of another component (Huhnt and Richter 2010: 26). Another construction process modeling approach was developed by König and Baling (2010) in the course of the research project 'Mefisto'. 'Mefisto' is a big research project in Germany, which aims to develop a visual platform for modeling, information and knowledge to support cooperative management in construction projects. König and Baling base their research approach on Huhnt's and Richter's modeling. They employ reusable process modules as templates for the construction process. These reference process modules are supplemented with composite knowledge to determine the sequence between the processes. Their approach can be used for the description of executed processes as well as for information processes (König and Baling 2010: 77). It is usually considered a more common approach in process research.

2.3 Linking Product and Process Data

The connection of product and process data is a major theme of various research projects. In the project 'ForBAU', for instance, a connection like this is realized in bridge construction to model a digital construction site. The digital construction site allows a simulation of construction sequences. The product model for the bridge as well as the construction sequence model consists of four levels. The construction methods constitute the connection between the product and the process model, so that on the fourth level of the construction sequence the activities occur. Every activity has an attribute of 'quantity'. This attribute is developed by the product model, and every activity is linked with the resources (labor forces, machines and material). The dependencies between the activities are determined by hard and soft constraints. (Dori and Borrmann 2010).

In a further research approach Tulke and Hanff (2007) have developed a method to generate a 4D model through the connection between the product model and the time schedule. This approach describes a process model. The process model contains the generation of a 'bill of quantities', which first is automatically determined from the CAD model and second should be completed manually. Further, resources are defined by the process model. The time schedule is connected with the 'bill of quantities' as well as with the resources. The 4D model is created by this connection. The connection between the time schedule and the 'bill of quantities' is rule-based. As a result, the determining advantage of this 4D modeling process is the reduction of the connection of the time schedule with the 3D CAD model. (Tulke and Hanff 2007).

3. Linking Product and Process Data in CiSmo

A construction project usually has a large number of involved enterprises. Each enterprise has its own view and own interests concerning the construction project. This fact complicates the development of a product model, which is useable in all project phases and for all persons involved in the project.

Current applications of comprehensive product models are developed and distributed under the term in Building Information Modeling (BIM). Eastmann et al. (2008, S. 8) state that the use of a BIM is dependent on the phase of the project in which the model is generated, and how well the collaboration of the project participants is functioning. They underline that a BIM can then be applied profitably, especially if only one enterprise is responsible for the building design and the complete construction process. Although in Germany such cases might be the minority, because of the small size of most German construction companies.

In the actual situation of the German construction economy it is difficult to realize the use of a comprehensive product model which is applied in all phases of preparation and execution of construction work.

Such a product model is first and foremost applicable for big enterprises, which work on various phases simultaneously. Chahrour (2007, S. 50) takes a critical view at the trend towards a complete product model. She states that such models tend to be too complex since more and more new aspects need to be integrated during the course of a project. The rising complexity makes the models uneconomical. Moreover Chahrour points out that, usually there are no participants in a construction project who have an interest in the entire content of a product model and they do not feel responsible.

For this reason, we decided to concentrate on the development of a process model which is only specialized for the phase of the preparation and execution of construction work. We did not integrate the process model into an overall product model. The process model can be combined with different CAD formats, theoretically. Therefore, the process model is independent from special CAD formats or CAD interfaces, like for instance IFC (Industry Foundation Classes).

The process model can be linked with three-dimensional CAD-models of buildings. The CAD-model consists of components which are instances of abstract component types. Each component type must be connected with one or several construction methods (see figure 1). This step is fully customizable. The user can select between construction method templates which consist of construction activities.

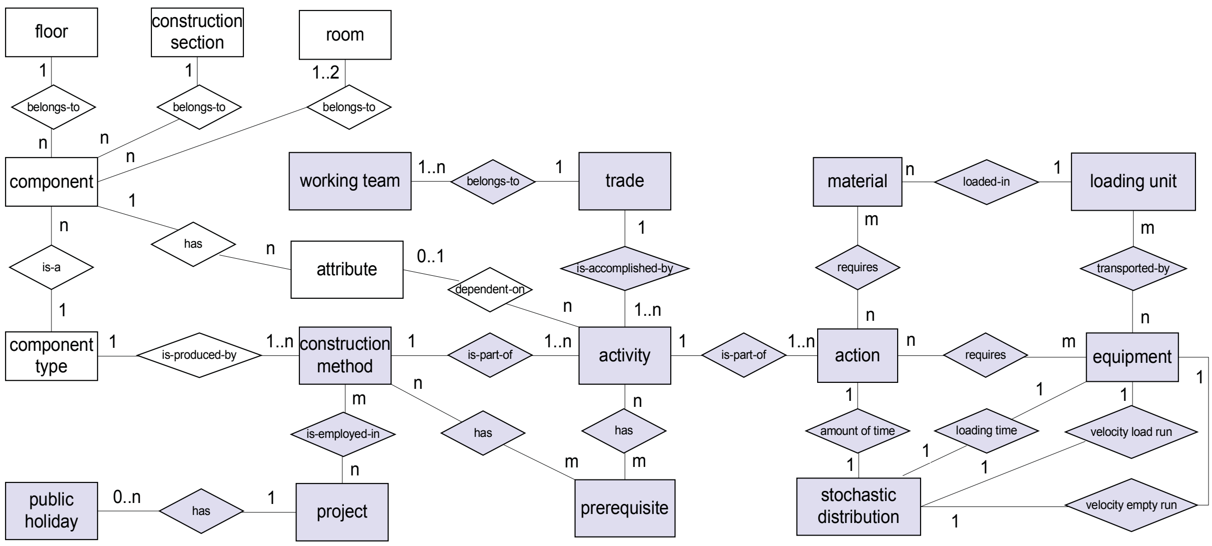


Fig. 2: Entity-Relationship diagram of the product (white background) and the process data (grey background).

An activity contains several actions and is associated with a certain trade. The actions of an activity are linked with the resource requirements. The process model contains three different resource types: the equipment, the material and the time used for the action. Several parameters, like for instance the time, could be specified as stochastic distribution. The quantity of the used resources depends on the volume, weight, length, surface or number of the processed components.

CAD-models usually have different levels of detail. This causes difficulties by linking the process with the product data. It is not possible, for example, to link the process ‘lay an electrical cable’ with a component if the electrical cables and installations are not part of the CAD-model. For this purpose, we introduced additional component attributes (see fig. 2). These attributes can be linked with the activities of the process model. The component ‘wall’ can be extended by the component attribute ‘contains electrical cables’. Only if an attribute applies to a component, the linked activity (e.g. “lay an electrical cable”) is executed (Kugler and Franz 2009). This way it is possible to add further details to the CAD-model. Additionally, a larger quantity of components can be instantiated from a single component type. It is not necessary to use the different component types 'walls with electrical installation' and 'walls without electrical installation'.

The sequence of the activities is set by certain prerequisites. The difficulty is to define these prerequisites in a way that they can be used for all instances of a component type. In order to facilitate this process we developed a template for the definition of prerequisites which considers spatial and chronological relations between activities. The spatial relations relate to the geometry of the building, consisting of the floors, the construction sections, the rooms and the states of the components. The chronological relations are modeled by task dependencies defined in DIN 69900. The user is able to determine one or several prerequisites for each activity and to define the conditions between activities for a whole class of components. Moreover, the user can define her or his own templates.

In reference to the modeling method of Huhnt and Richter (2010), in CiSmo it is necessary to define the result of the activity which is the prerequisite for the activity at hand. The result of an activity is available as state of a component. The prerequisite for an activity relates to the state of all components of a component type in one section or one room on a certain floor. The construction sequence can therefore be described by horizontal (sections and rooms) and vertical (floors) geometric relationships in CiSmo. These geometric relationships are specified relative to the location of the component for which the activity is to be executed. For example, to express the fact that the load-bearing walls below the current construction section need to be concreted two days before an activity in this section can start, the following terms are used: 'load-bearing wall concreted', 'this section', 'previous floor', 'end-beginning 2 days'. If no previous floor exists, the prerequisite is automatically ignored by CiSmo.

Our process model has two kinds of prerequisites:

- The **workflow direction** describes an organizational dependency. It is used to determine the sequence of the activity in the sections and floors of the building.
- The **dependency relationship** describes technical dependencies between the activities.

Figure 3 and figure 4 illustrate the different types of prerequisites.

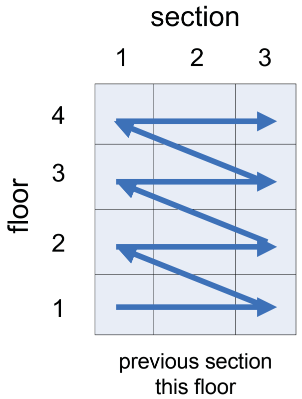


Fig. 3: Example of the workflow direction

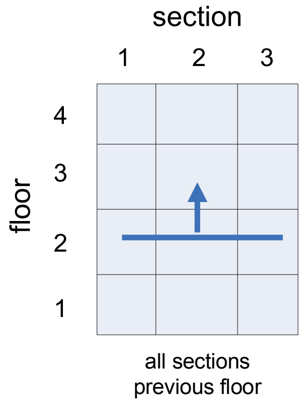


Fig. 4: Example of the dependency relationship

The starting point of the arrow is located in the section and floor where the activity of the prerequisite has to be executed. The end point of the arrow points to the section and the floor where the activity should be started if the prerequisite is met. The terms below the structure of the building (e.g. 'previous section' and 'this floor') describe the sections and floors where the prerequisite of the ongoing activity is located (see figure 3 and 4).

4. Implementation of CiSmo

The modeling environment CiSmo was implemented based on the described process model. CiSmo can be used to develop agent-based simulation models in the CAD environment Architecture. Architecture is based on the CAD environment AutoCAD from Autodesk. The building model in AutoCAD Architecture consists of 3-dimensional components.

4.1 Structure of CiSmo

CiSmo is directly integrated into the menu of Architecture. Via the menu the user gets access to several application windows. By using these application windows the process model can be parameterized. CiSmo automatically reads all components from the building model. The user links the component types with the customizable construction methods. Afterwards, the components are saved with all relevant parameters for the simulation in a simulation model. The complete modeling and parameterization of the simulation is carried out in the CAD environment. Thus the CAD environment is extended to an editor for simulation models.

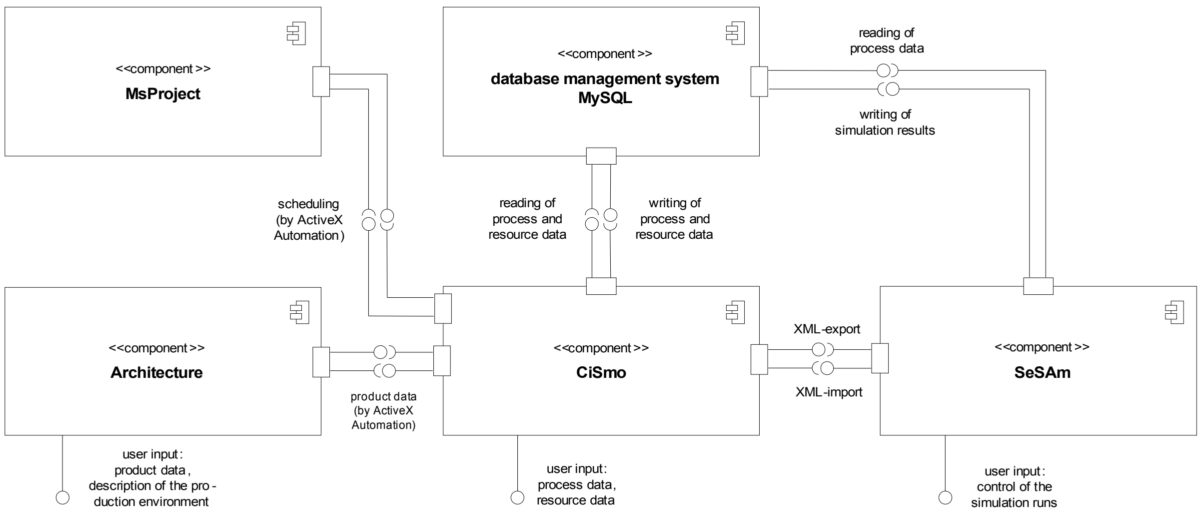


Fig. 5: UML component diagram of the simulation system

The component diagram illustrates the structure of CiSmo (see figure 5). The components symbolize the different elements of the simulation system. They communicate by defined interfaces. Interfaces are illustrated in the component diagram by ball and socket symbols. The components are visualized by rectangles with a small component symbol in the right upper edge.

The data of the process model are saved separately in a MySQL database. The advantage of storing the data in an external database is, that the data can be linked with all major CAD formats. Additionally, the building and the process data can be processed independently. Because of the separate storage the process data can be used for new projects as well.

The experiments are carried out in the agent-based simulation environment SeSAm (**Sh**e**ll** for **S**imulated **A**gent **S**ystems). The simulated agents access the data of the process model via a SQL-interface during the runtime of the simulation model. In this way, they can use the process knowledge that they need for the execution of the construction activities (Kugler and Franz 2009: 191). So, the most current data is always available for simulation.

The simulation model is stored in the open data format XML. Therefore the parameters of the components, the building site facilities and the construction sections can be transferred from the building model into the data structure of the simulation model directly.

As result of the simulation runs and to proof the consistence of the process data, it is possible to generate schedules by using CiSmo. The structure of the building model, the process data and the description of the production environment is used to create the schedules automatically. The schedules are generated in Microsoft Project by using the ActiveX automation.

The results of the simulation runs are stored by SeSAm via the SQL interface into the MySQL database. CiSmo uses these data to build the schedules.

4.2 Technical Implementation

VBA (Visual Basic for Applications) was selected as API (Application Programming Interface) for the integration of CiSmo into the graphical user interface of Architecture. Compared to other APIs (like ObjectARX and AutoLISP) it provides the advantages of higher speed in program execution, a high usability, the compatibility with Windows and other Microsoft software (e.g. Microsoft Office). In addition, it provides the possibility to quickly develop a prototype (AutoCAD 2009).

By using VBA we implemented the additional menu item 'Simulation' which is integrated into the graphical user interface of Architecture. The menu grants access to application windows for the manipulation of the process data. Additionally, we programmed VBA procedures and class modules to read the building and component parameters.

The functions to access the data structure of the simulation model were implemented by using a data binding tool. Based on a XML schema definition file the data binding tool automatically generates Visual Basic (VB) source code. The source code contains procedures and class modules for manipulating a XML file which is based on the XML schema definition. By using VB we compiled the source code to a dynamic link library (dll). This library can be used in the VBA-IDE (Integrated Development Environment) of Architecture.

4.3 Program Sequence

The program sequence is structured by the sequence of the menu items of the additional menu 'Simulation'. Via the menu items the application windows for the parameterization and the generation of the simulation models can be accessed.

Figure 6 illustrates the standard program sequence in an UML activity diagram. Initially, common project parameters, like for instance the work duration, the beginning of the project or public holidays, are entered via an application window. Afterwards, the used resources (equipment, material and staff) for the process simulation are defined. The production environment is specified by placing the building site facilities and the construction sections. They are directly drawn into the building model in Architecture.

The process modeling is subdivided in the phase of the selection of the construction methods and in the definition of the construction methods. The application window for the selection of the construction method is used to link the construction methods with the building components. By using the application windows for the definition of the construction methods the specification of the activities and the actions are carried out.

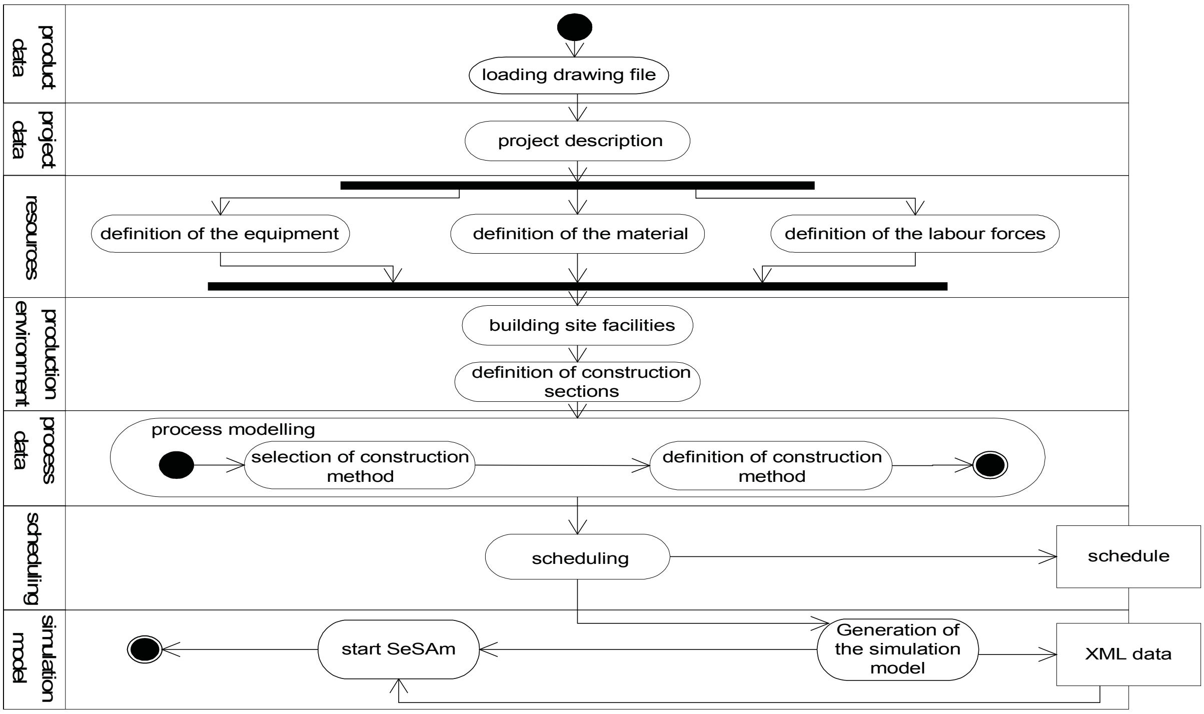


Fig. 6: UML activity diagram of the program sequence

Based on the building model and the data of the process model, CiSmo automatically creates schedules. Before carrying out the simulation runs the user is able to proof the consistence of the process data and the sequence of the activities by using these schedules. Finally, the automatic creation of the simulation runs take place, based on the same data.

5. Conclusion

CiSmo was developed for the tasks of preparation and execution of construction work. It has already been tested with two different construction projects, a nursing home for the elderly and a small passive house residential area. We were able to express all occurring relationships between the different construction activities using CiSmo's presented modeling method.

The modeling method is suitable to define relationships that result from constructive dependencies as well as for the description of the organizational construction sequence (e.g. first the concreting of the columns in section 1, next the columns in section 2, etc.).

In the event of that different components instantiated from one component type have to fulfill various functions inside the building (e.g. various structural functions), problems occurred in the practical test. The reason is the components underlie different technical dependencies. Consequently, components with different functions have to associate with different component types.

Furthermore, not all items of the bill of quantities could be mapped in the process model without any problems. Many small items of the bill of quantities could only be integrated in the simulation model by creating lots of additional component attributes. By using CAD-models, which include all details of the building, the modeling process could be accelerated. That is because all items of the bill of quantities could be directly linked with the building model.

We thank the DFG (German Research Foundation) for the financial support of this research project.

6. Further Work

Any simulation study would consist of three phases: "Simulation Preparation", "Simulation Execution" and "Simulation Evaluation". During the "Simulation Evaluation" phase the simulation results are analyzed and the process data is manually adjusted in an attempt to satisfy the project's economic concerns. With respect to the adjusted process data, the simulation experiment is executed again. As for the Evaluation phase, it is a cyclic process, which means that after each simulation execution the results are evaluated again, and the process data are adjusted and then executed. This cyclic process ends only when the project's concerns are satisfied, so it's apparent that these manual adjustments and trials are exhaustive in regard to time and effort.

The functionality of the proposed CiSmo model covers both the Preparation and the Execution phases, whereas the Evaluation phase is left as a manual task. As a result, the researchers at the Institute of Construction Management at the University of Kassel are discussing the automation of the evaluation phase.

The new proposed approach is to develop an optimization methodology within the simulation study in order to automate the Evaluation phase. This methodology consists of an "Optimization Approach" and an "Automation Approach". The optimization approach is responsible for guiding the simulation run during the execution process in order to achieve a better "optimized" construction schedule based on several predefined economic criterion. The main economic aspects of a construction project are: planned costs and planned duration. Our goal is to keep the project's cost and duration as minimum as possible by prioritizing the execution of activities along for example the critical paths, and by increasing the utilization of the project's resources which are; Machines, Workers and Materials.

On the other hand, the automation approach is responsible for adjusting the process data, generating different simulation's experiments and situations, and then demanding the execution of each new situation automatically. It's suggested that the process data can be modified based on the experience of the previous finished construction projects and thus different simulation's experiments can be generated. Furthermore, the number of the available resources in each experiment will be changed according to the value ranges, which are defined in the process model, and different new simulation's situations are generated accordingly.

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AUTOMATIC GENERATION OF COMPLEX BRIDGE CONSTRUCTION ANIMATION SECTIONS BY COUPLING CONSTRAINT-BASED DISCRETE-EVENT SIMULATION WITH GAME ENGINES

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ABSTRACT: *Construction animations make it possible to conduct detailed analyses of geometric constellations in dynamic construction processes and therefore form an excellent basis for feasibility studies. Construction animations are, however, usually generated manually and typically time-consuming and therefore costly. In this paper we introduce a new method for automating the generation of construction site animations. The method is based on "animation snippets" which represent individual work steps that can be assembled to form a complete animation sequence. The animation snippets are parameterized with respect to geometry and time so that they are adaptable to the specific conditions of a particular construction process. In the proposed concept, these parameters are set by the output of a constraint-based discrete event simulation. The animation snippets themselves are realized using a game engine. The entire methodology is illustrated using the example of a bridge construction process. An animation snippet used to model a crane transporting concrete is discussed in detail.*

KEYWORDS: *construction site animation, game engine, discrete event simulation, preparator, animation snippet, crane animator, ray-tracing*

1. Animation of construction processes

Virtual reality animations of construction sites combine comprehensive 3D models with dynamic information, i.e. they display the movements of individual machines, vehicles or even workers. With the help of such animations, it is possible to conduct detailed analyses of the geometric constellation of the construction site as well as to investigate the construction processes. Feasibility studies conducted before the construction project starts make it possible to identify problems in the planned construction workflow, including potential clashes between machines and/or building elements as well as erroneous sequences of work steps. Thanks to the advanced immersive features of modern VR systems, the user can be observe the construction site from almost any position, providing a better understanding of the construction workflows.

1.1 Process of automation

Today, construction animations are typically produced manually in a laborious and time-consuming process. Their high cost of production means that they are not an option for most construction projects. This is closely related to the fact that construction projects are in most cases unique, as both the resulting buildings as well as the conditions vary from project to project. In this respect, the construction industry differs from other sectors where the number of items produced is much larger and additional effort in the pre-production phase pays off if it is able to improve the production process. To make the generation of animations more economical for the construction industry, a higher degree of automation is necessary.

Our approach for achieving a higher degree of automation consists of three phases (Fig. 1):

- First phase (preparations): A 3D model of the building is enhanced with process information through the application of construction methods. This is achieved using a dedicated preprocessing toolkit called Preparator (Wu et al., 2010, Dori et al. 2010). The output of the Preparator is a large set of individual work steps necessary to erect the respective construction.
- Second phase (simulation): A detailed process simulation is run to find a near optimal sequence of construction processes. As a result, each work step is associated with its calculated start and end date.

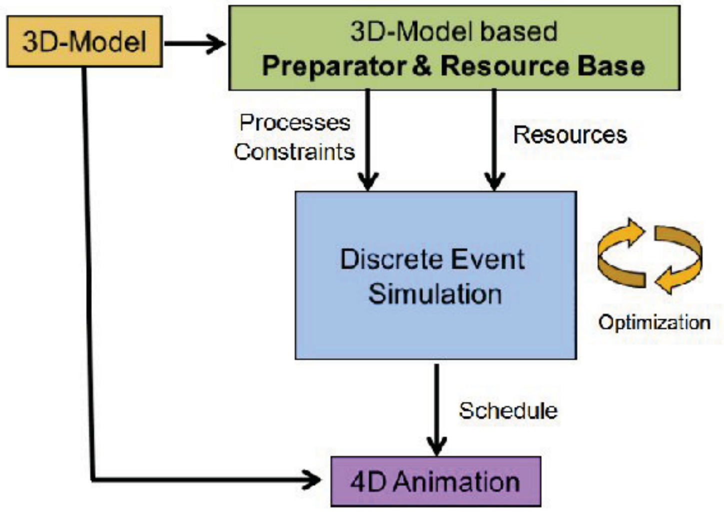

Fig. 1: Schematic overview on the components used for the automated generation of construction site animations

- Third phase (animation): An animation of the construction processes is generated using a game engine. To facilitate automation of this phase, *parameterized predefined animation snippets* are created for individual tasks, e.g. move, turn object, etc.

2. Preparations

To visualize an animation of the construction processes, a detailed *3D model* is required that comprises the required construction components as well as the environment of the construction site. To automatically create an animation, three *primary parameters* have to be considered: *what* component should be built *when* and *how (animation type, e.g. movement, rotation)*. The *secondary parameters* are those required to create the defined animation type and can differ from one another in each case, e.g. different parameters are needed for a linear movement than for rotation.

2.1 What, when, how?

The definition of the parameters that concern the *what*, and in part also the *how*, is realized using a toolkit called *Preparator* (Wu et al. 2010, Dori et al. 2010). With the help of this software the user assigns predefined construction methods to individual components of the 3D model, implicitly defining individual *works steps* as well as their resource and precedence constraints. In a later phase (animator), these work steps will be associated with a set of *animation snippets* used to visualize the construction of the respective component. An animation snippet models an individual action that can be well defined (movement, rotation, scale, create new object, change transparency, etc.). A work step is therefore usually composed of a number of animation snippets, as is the case for *fill with concrete*, for example:

1. Move concrete mixer to the construction site Ű 2. Take funnel hopper from the storage area Ű 3. Move funnel to the concrete mixer Ű 4. Fill the funnel with concrete Ű 5. Move the funnel above the object Ű 6.a Release the concrete from the funnel, 6.b Fill the object Ű 7. Move funnel to storage area/delete funnel Ű 8. Move concrete mixer (leave construction site).

To define the dependencies and requirements of the individual work steps, they are connected by different kinds of constraints. The two basic categories are:

- *Precedence constraints*, which are necessary to define sequential time dependencies between work steps, e.g. formwork and reinforcement has to be assembled before filling the item with concrete.
- *Resource constraints*, which define the required resources to complete the respective work step, such as manpower, machines, materials etc.

As input, the Preparator uses a 3D model of the entire construction stored in VRML format. When the user selects a construction method for an individual component and defines the work steps and their associated constraints, the Preparator isolates the VRML code of the respective component and saves it in a new file (2). This is required for later animation, where scenes are composed of individual objects that are moved independently of each other.

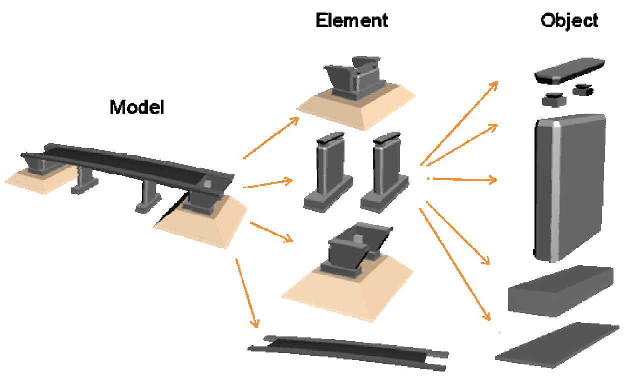

Fig. 2: Decomposition of a 3D model to elements and objects

The "when" parameters for the animation, i.e. when each individual work step starts and finishes, are derived by a simulation of the construction process. To obtain accurate results it is necessary to predefine and import not only the work steps but also the *available resources* into the simulation.

2.2 Resources

The Resource Base is an extension of the Preparator. With this tool the available resources can be defined and exported for use in the simulation. These resources play an important role in the simulation: the required workers, machines and materials are selected and reserved from the stock of resources available for each individual work step during construction, and the duration of a single work step is calculated based on the capacity and performance of the workers and/or machines. While one work step is being undertaken, the resources used are therefore not available for other purposes. The Preparator defines the parameters for the animation of a machine, worker or material. During simulation, an animation snippet is connected with the resource (3D object) for the duration of the period that the simulator determines it is required.

The file exported from the Preparator and the Resource Base serves as the input data for the simulation, and later (extended with the results of the simulation) also for the animation.

3. Constraint-based discrete-event simulation

As described above, one of the most important parameters for the animation snippets are the start and end dates of the individual work steps. For small construction sites, these dates can be calculated fairly accurately with conventional available schedule optimization techniques. But for large-scale construction projects, the creation of an optimized schedule becomes difficult or even impossible. In such cases, modern simulation techniques can be very effective and lead to both time and cost savings.

3.1 Concept of the simulation

Conventional approaches for simulating construction processes employ the discrete-event based method (AbouRizk et al. 2010). The discrete-event simulation technique was originally developed for the mechanical engineering and automotive industries where the product components typically travel along fixed assembly lines and are handled by workers or processed by machines at specific points (workstations). Construction projects, by contrast, do not have fixed activity sequences but are much more dynamic and spontaneous. To incorporate this quality into discrete-event simulation, a *constraint*-based extension has been developed (Beißert et al. 2008a). The constraints define pre-requisites for the execution of a work step. These include the required resources or technological dependencies (see Section 2). If there are several executable work steps possible in one segment of time, we can select one either randomly or according to a certain strategy (e.g. as fast as possible, cost saving etc.). Strategies are implemented by using *soft-constraints* (Beißert et al. 2008b) which make it possible to define priorities in the order of executable work steps. To find a near optimal solution for the schedule a Monte-Carlo analysis is performed, either with the same, or with different process configurations (resources, strategies).

3.2 Result of the simulation

In the first step, the simulation program reads in the file exported from the Preparator, importing the work steps and resources as well as precedence and resource constraints. The work steps are created in the simulation as *work packages* which are connected to their *attributes* such as required resources, properties of the object etc. The checking process of the resource constraints as well as the calculation of the duration of the work step is performed using these attributes (volume, pieces, area etc.), and the corresponding attributes of the resources (class, performance etc.). When a work step is executed, the start and end dates are determined and saved back into the same file that was imported at the beginning of simulation. As a result, each individual work step is now associated with a part of the 3D geometry in the model, a start and an end date. What remains is how it should be animated.

4. Animation

To create the animation snippets a tool called *Animator* is used. It loads the work steps, reads in the information about the animation, and using the necessary parameters creates the respective animation snippet. This snippet will be stored in a list and as the animation proceeds the animator checks which animation snippet should be started. In this way a complete animation of the construction site can be created.

By way of example, we shall examine the animation of the process of concreting and the associated crane movements. In many construction projects, these processes are critical to avoid any potential spatial collisions and their impact on the overall project duration. A detailed investigation of these processes can help reduce costs and ensure timely completion of the project.

4.1 Game engine

For creating construction animations we use Irrlicht, an open source game engine [Irrlicht]. In general, game engines are development platforms which are highly optimized for visualizing and interacting with 3D scenes. They usually support real-time rendering and integrate a physics engine for real-time collision detection, ray-tracing, gravity field simulation, etc. These features can also be employed for realistically visualizing and animating construction site processes, enabling the user to be placed virtually in the model. The advantages of using game engines for visualizing construction processes have been reported in (Yan et. al. 2011), where Microsoft XNA was used for interactive architectural visualization, and in (Nikolic et. al. 2010), where the same engine was used for the Virtual Construction Simulator, an educational tool for teaching students construction scheduling tasks. ElNimr and Mohamed (2011) used Blender and TrueVision 3D to create a simulation driven visualization of construction operations.

4.2 The animation

4.2.1 Parameters

The *primary parameters* of an animation are those that apply for all the animations: what component is animated, when, and how (Section 2.1). While the Preparator defines the objects and the simulation the time parameters, the "how" parameters are defined by the Animator. The necessary parameters of each animation snippet are the *secondary parameters*. These can be coordinates, rotation angles, state of the object (light, reflection, transparency, diffusion etc.), whether it follows an object and so on, i.e. parameters that are needed to realize the animation. They are stored together with the work steps in an XML file exported from the Preparator, and are extended by the results of the simulation. The Animator reads in this file and the included work steps. It then loads the connected 3D object of the work step into the scene, and creates the appropriate animation snippets using the predefined parameters. When the process finishes, the animation can be started. Using this concept the manual effort of producing an animation is significantly reduced by dramatically increasing the degree of automation. The user needs only define the connection between the 3D object and the construction process, define some extra parameters for movements or rotations, and to initiate the simulation and the animation. The remaining steps all happen automatically.

4.2.2 Hierarchy

We define five levels of animation (Fig. 3) according to the hierarchy of the construction processes generated using the Preparator (Level of detail approach – Wu et al. 2010, Dori et al. 2010). The basic level of the animation is the *animation snippet* (Level 5). A snippet always changes one secondary parameter of the animated object, so it can mean movement, rotation, scale, following another object etc. A group of these snippets together comprise an *animation set* (Level 4). These sets visualize a single work step.

Animation sets / work steps are assembled to form an *animation package* (Level 3) which visualizes a complete construction method that shows how a sub-element is constructed (e.g. create an object made of reinforced concrete). At Level 2 *animation packages* are combined to form *construction elements*. This level is used to visualize the construction of complete elements, for example an entire pier or an entire abutment. At the top level (Level 1), these elements are then connected to form a *complete construction site animation*.

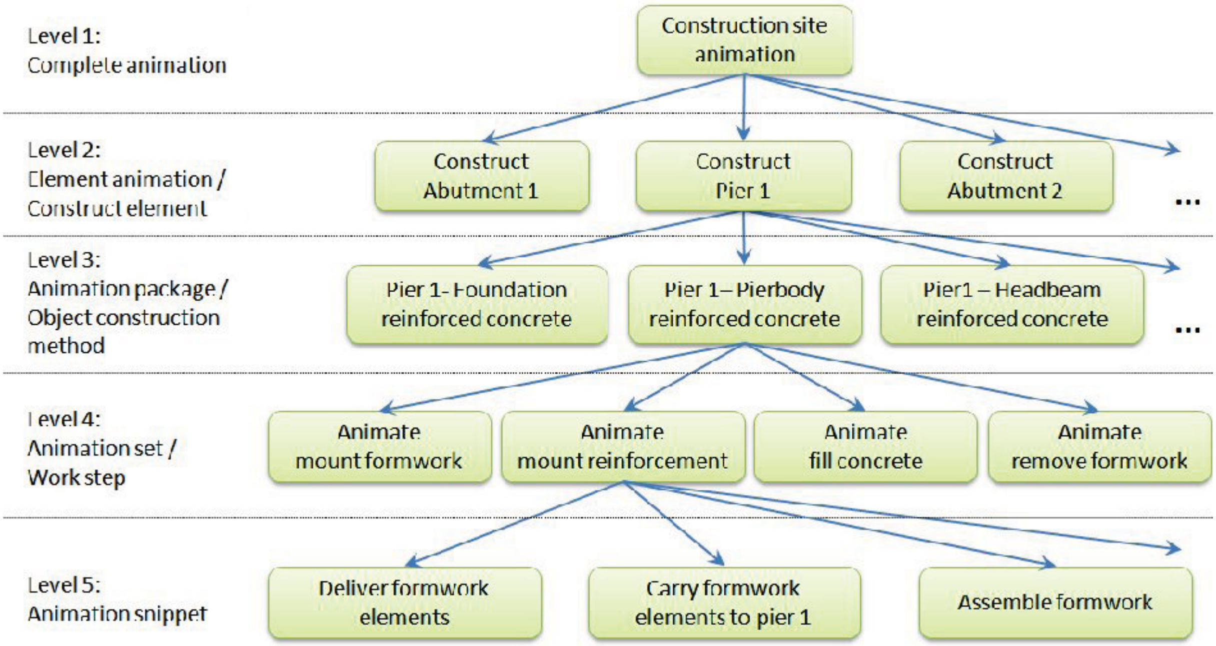

Fig. 3: Hierarchic system of levels of the animation

4.2.3 Animation snippets

An animation snippet is the basic element of the construction site animation and the only element of the hierarchy which is actually animated. The elements on higher levels are formed by assembling combinations or sequences of lower-level steps and do not add additional information to the animation. As an example we show the sequence of animation snippets for the construction method *create an object made of in-situ reinforced concrete*:

1. Delivery of the formwork elements: truck drives to the construction site: normal 3D-movement or Follow-Spline animation (Spline has to be predefined).
2. Transfer the formwork elements one by one to the base object: using Crane animator (section 4.3).
3. Assemble formwork: appearance of the formwork supporter elements / Crane animator.
4. Delivery of reinforcement: truck drives to the construction site: 3D-movement or Follow-Spline.
5. Transfer reinforcement to the base object according to a predefined assembly order: Crane animator.
6. Retrieve a funnel hopper for concreting works from the storage area: Crane animator.

7. Drive concrete mixer to the construction site: 3D-movement or Follow-Spline animation.
8. Transfer the funnel hopper to the mixer: Crane animator.
9. Fill the funnel with concrete: size-changing animation.
10. Transfer funnel hopper above the base object: Crane animator.
11. Filling concrete:
    a) Release concrete from funnel: size-changing animation.
    b) Fill concrete to the base object: size-changing animation.
12. Transfer funnel hopper back to the truck: Crane animator.
13. Loop steps 8-11 until the base object is fully filled with concrete.
14. Return funnel back to storage area: Crane animator.
15. Drive concrete mixer away: 3D-movement or Follow-Spline animation.
16. Curing time: change surface reflection.
17. Dismount formwork: Crane animator – move formwork elements back to storage area.

An animation snippet is used for each of the individual steps. In this case the construction method (*animation package*) comprises 17 animation snippets. Following the hierarchy, the construction method is made up of four work steps (*animation sets*): *mount formwork* – *mount reinforcement* – *fill concrete* – *remove formwork*. The *mount formwork* animation set is comprised of the animation snippets 1 to 3, the *mount reinforcement* animation set of the snippets 4 to 5, the *fill concrete* set of the snippets 6 to 16, and the *remove formwork* of snippet 17. Accordingly, different work steps may comprise different numbers of animation snippets. The animator knows which animation snippet has to be created for each work step, so all these animation snippets will be defined automatically during the file importing process.

The list provides an indication of the kind of tasks an animation snippet can visualize. The 3D movement and the Follow-Spline animation snippet play important roles. These animation snippets are mostly used for animating vehicles, machines and workers. A 3D movement is a straightforward linear movement between the start and the target point. The Follow-Spline animation is similar, but instead of moving linearly the object follows a spatial curve. It is used, for example, when the surface of the terrain is not flat, or a road is not linear.

The next generation of this animation snippet is the *surface following movement* snippet. For this, gravity field and collision detection methods must be implemented in the model. This kind of animation is familiar from first person shooter games, where the camera (viewpoint) follows the terrain at a predefined height as the user moves (the first-person). This capability is used to ensure that trucks and other machines will automatically stay on the surface, or drive between points on the surface of the terrain.

Another very important animation snippet component is the crane animator. The crane plays a significant role on the construction site and a special tool is created to automate and control the animation of the crane movements.

4.3 Crane Animator

The crane animator facilities the automatic creation of an animation transporting an object from its place of origin to a target coordinate by means of a tower crane. The carrying process is executed along a predefined path, but with real-time collision-detection and path-correction during the ongoing animation. Collision detection and path correction is important when there are other objects moving on the construction site (trucks, machines), or where further cranes are also operating within the same workspace. The input parameters of the tool are the start and target coordinates of the object as well as the technical properties of the tower crane: height, length of the jib, turning speed of the jib, speed of the trolley, lifting speed. Our tool is dedicated to visualize and find a possible spatial path for the crane movement, not considering physical parameters like forces in the cable etc. as discussed in (Chi et. al. 2010).

4.3.1 The structure of the tower crane

To be able to automate the movements of a tower crane various aspects have to be taken into consideration. The structure of the crane model has to be defined hierarchically to be able to follow every possible movement of the crane and its components. For example when the jib turns the trolley and the hook have to move with it automatically, but not vice versa. This is realized by a hierarchic *master-slave mechanism*, according to the forward kinematics, where the model has an ordered chain structure (Chi et. al. 2007). If a chain element is moved, the sub ordered chain elements will move with it, but not vice versa. The master of the model is the *mast*. All the other parts are defined as the slaves of the mast. A slave object means, if the master moves, the slave moves automatically with it, but if the slave moves, the master stays unchanged. The first slave is the *jib*. The turning point of the jib is located at the section point of the centre lines of the jib and the mast. The next part is the *trolley*, it moves forward or backward along the jib. Setting the trolley as the slave of the jib only results in a rotation when the jib turns, so the relationship has to be extended to also recalculate the new position of the trolley. The *hook* is the slave of the trolley, connected to it with *cables*. The cables are special in that they are slaves of both the trolley and the hook: the start point of the cable is the slave of the trolley; the end point is the slave of the hook. So if the hook moves up or down, the length of the cable changes. When the trolley moves, then the cable must also move along with the hook, and when the hook swings out, the cable swings as well.

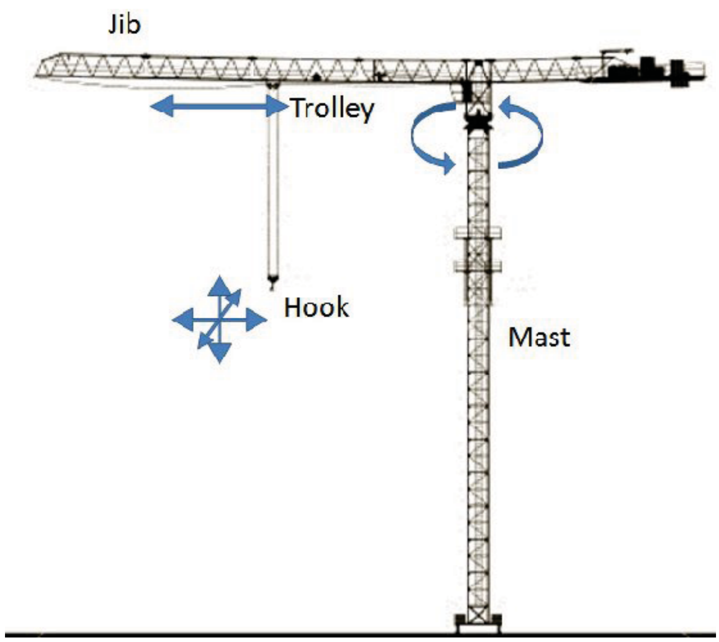

Fig. 4: Basic elements and movements of a tower crane (picture source: iStockphoto)

4.3.2 Carrying process

First the tool checks if both the start and target coordinates are within the range of the crane. If so, the carrying process can be started. The jib turns above the object, lowers the hook and connects the object to it. At this moment the object becomes the slave of the hook. When the hook moves, the object now follows it in every direction. The tool checks the height coordinates of the start and the target points, and lifts the object above the level of the higher one. Then it tries to predefine a possible way between the start and the target point. It checks which is nearer to the crane, and moves the trolley to the nearer position. The trolley always tries to be as near to the mast as possible, so if the start point is nearer, the trolley will stay where it is; if the target point is nearer, the trolley will move to the smaller distance from the crane (Fig. 5 left). The predefined way will be checked for collisions (ray-tracing).

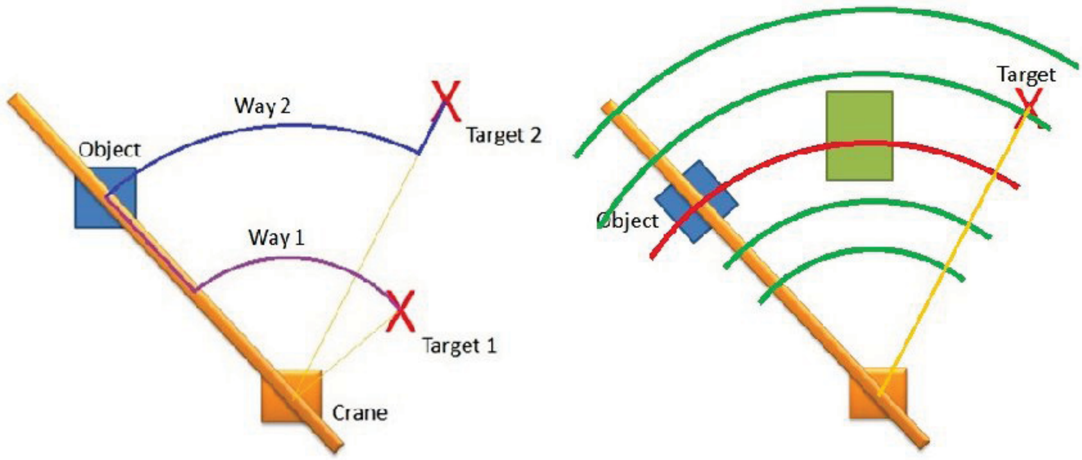

Fig. 5: Carrying ways depending on the distances between the start and target points from the crane (left), and identification of possible collision-free paths using ray tracing

There are two existing general methods for collision detection. The first group can determine whether a collision exists or not, the second one can also return the distance to the nearest possible collision. The second group requires more computation time, however "knowing the shortest possible collision distance can eliminate unnecessary collision checks within the collision free region, significantly reducing the computational time…" (Lai et. al. 2009). To reduce calculation time even more, different strategies are used like usage of different bounding objects (Lai et. al. 2009) or hierarchical ordering of the objects (Chi et. al. 2010). Our ray-tracing approach is somewhere between these two groups. We are attaching different rays to a moving object and check if this ray (with predefined length) is colliding with another object or not, without checking the distance. Doing so, a collision can be predicted, and the path of the object in time before the collision modified. In case of the predefined path, the path will be converted to a ray and checked if it collides with anything or not. If it is collision-free the movement of the object can be started. If there is an obstacle in the way, a new path will be determined. The area between the object and the target will be discretized with circular lines in the height of the movement looking for collisions (Fig. 5 right). The simulator chooses the nearest collision-free circle from the predefined path and sets this as the new path (when it does not find any free circles, it goes to a higher level and check the circles again). The trolley has to move to this point first along with the object; only then can the jib start to turn in the direction of the target. When it arrives, the trolley moves above the target point, lowers the hook, and places the object at the target coordinates. Consequently the basic predefined horizontal movement is always composed of one linear and one circular component, when it is corrected from two lines and a circular part.

While transporting the object, a second real-time collision detection and route correction routine is performed in order to find and evade other obstacles on the path. These obstacles are mostly moving objects such as vehicles or objects placed by other cranes that were not present when the path was defined, or even the other cranes. For detecting obstacles a ray-tracing technique is used. As soon as a potential collision is detected the crane animator recalculates the path of the object until it is collision-free again, and follows this new path.

The same technique is used for the cranes to detect other cranes in their path. If one receives a message about a possible future collision, the crane stops and tries to communicate with the crane animator of the other crane (which also registered the possible collision). The one with higher priority continues its movement, the other one has to wait, or move back to allow sufficient space for the other to pass. When both cranes have equal priority, one is chosen at random and the other has to wait.

An important factor of the animation is the time interval of a frame. When the crane movement is visualized, the object moves along the predefined path with collision detection and possible path correction undertaken on a frame-by-frame basis. The more frames (= the shorter the time interval) there are to visualize the crane movement, the greater the number of "discrete" steps and the better the chance of detecting a collision. If the time interval between two frames is too great, there is the chance that the animator moves unnoticed through an obstacle between frames. This must obviously be avoided at all costs. Further investigations are necessary to identify the minimum number of frames for crane movement.

5. Summary

In this paper we have introduced a novel approach for automating the process of generating construction site animations. Using the Preparator tool, the basic input data for constraint-based discrete-event simulation and subsequent animation is created by assigning predefined construction methods to individual 3D objects. The simulation is used to determine a possible time schedule, including start and end dates for each individual work step. The animator uses this information in turn to start and stop so-called animation snippets. These represent individual work steps and are assembled to form a complete animation sequence. Animation snippets are parameterized with respect to geometry and time so that they can be easily adapted to respective conditions of a specific construction process.

For the visualization, the game engine Irrlicht is used. Game engines are highly optimized for visualizing and interacting with 3D scenes and usually support real-time rendering and as well as the simulation of basic physical phenomena.

Since cranes play an extraordinarily important role in construction processes, a crane animator tool has been developed that automates the transport path calculation and its subsequent visualization. Using ray-tracing technology in each visualized frame it performs collision detection and if necessary corrects the predefined route. The next step of automation will be to couple simulation and animation. This will allow the user to steer the simulation using the animation, e.g. to pause the simulation, choose the next executable work step, modify the position or operation of a machine or worker, and the simulation will then react accordingly to the changes in the visualization.

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AUGMENTED ENGINEERING MODELS ON THE WEB

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ABSTRACT: *In today's world collaboration in project management is becoming increasingly more global. As enterprise web portals are becoming more functional, they can provide a single immediate point of access for multiple unconnected sets of databases and information systems to users from different countries using different types of devices.*
Despite the recent advances in browser technology, rendering 3D content on the web is still difficult. Today there is still no de-facto standard for displaying 3D models within browsers and this is even more problematic in the AEC sector, as rendering engines are not designed to work with the design drawing formats. Previous research papers have focused on the collaborative design only and there is a gap in knowledge in the areas of handover and operation phases of projects, where various sets of information need to be exchanged efficiently. In this context our research proposes a concept of an integration platform, where data, documents and model design data are tied together by using the Handle System – a component of the Digital Object Architecture.
This paper is part of the on-going research project to leverage the use of current Web3D technologies for displaying engineering 3D models on the web portals to facilitate collaboration and integration of different information and knowledge sets. The proposed solution for delivering model data to the browsers should be able to support as many existing technologies (DOM, CSS, JavaScript, HTML5, etc.) as possible. We are envisioning the functioning system to be useful for oil and gas and heavy civil engineering industry where collaboration between contractors and their supply chain is crucial for the successful project implementation and where the owner/operator wants to have as much data as possible for the plant/building operation, maintenance and shutdown.

KEYWORDS: *augmented engineering models, Web3D, information integration, digital object identifiers.*

1. Introduction

Traditional engineering information integration approaches are usually based on relational databases. Practice shows that such systems often do not perform up to the client expectations, are expensive to scale and still require custom solutions to be implemented, to deliver the user experience that was promised. With the advent of cloud computing platforms, designed to scale efficiently and major public information providers implementing custom data storage mechanisms, the need to revise information integration frameworks becomes evident. We review current issues in integrating engineering information and also propose to include knowledge integration, as it can be treated as another dimension to the existing data.

Increasing requirements for different companies participating in a single project to collaborate on the same data sets only makes data integration task more difficult. Project managers and engineers want instant and convenient access to information to be available from different parts of the world on a multitude of devices. Globally available and fast Internet access also means that information is now expected to be retrieved quickly and efficiently. Since a lot of companies already have and are constantly improving their enterprise portals, they are valuable information hubs to access, manage and even visualize engineering content. Thus our focus is to enable efficient information access from web portals utilizing the latest web standards and technologies.

Part of the engineering content is 2D and 3D design data, which in global practice has proved to be difficult to manage. Presenting such information in web browsers is even more complex, as there are no standards for 3D graphical content on the web and most solutions to this issue include creating custom proprietary plug-ins. While this does provide an access to the GPU resources, plug-in approach introduces the whole new set of issues. It is difficult to predict which technologies will become obsolete; however our research has focused on one existing 3D content presentation solution, which seems to be the most compatible with the existing standards and new technologies. Our aim is to combine the results of these research topics to propose an efficient information integration platform, able to deliver 2D and 3D engineering models along with the accompanying data to the web browsers.

2. Background

2.1 Knowledge Integration

2.1.1 Data integration

Many companies in the current industry deal with the fact that the information is dispersed between multiple systems. Public web search engines are mostly useless if information needs to be retrieved from internal sources – documents, files or databases which do not have globally available access points. Therefore such information needs to be managed, cleansed and indexed separately. In the oil and gas industry where a plant operator may be responsible for delivering timely information to the owner and at the same time gets information from contractors, sub-contractors and designers, the need of fluent information exchange is only increasing.

As information is delivered to the managing organization, several issues arise. Information coming from different sources usually comes in different formats and needs to have different importing/transformation routines. Companies often employ the concept of a staging area system or operational data store (Brazhnik and Jones 2007) for an intermediate step, where data is cleansed, validated, merged and then usually pushed to storage systems like data warehouses and document management systems.

The other issues with the data integration lie within the semantics of the data. Since data is coming from multiple suppliers, the same concept may have different meanings in different companies or even in separate branches of the same company. Ontologies are used in research and global practice (Wache, et al 2001, Kalogerakis, et al 2006, Lima, et al 2005, Anon., 2011f) to map different datasets to classify and map information semantics.

It is also very likely that data pieces will have different identifiers, even if they refer to the same physical or virtual object. Digital object identifiers are already used to create a globally accessible, secure system for identifying and finding books, documents, magazines or other published articles on the web. Digital object identifier records usually contain metadata with additional identifiers used in referenced systems and a URL for accessing the object over the web (Paskin, 2009) and therefore such system could be used to map all the available identifiers to a single global identifier.

Key process in the AEC industry is the Building Information Modeling (BIM). Having multiple international standards it is a conceptual way of creating and managing various building data during the project life-cycle. It is a steadily growing area as more and more companies realize the benefits and integrate model data with the additional non-design information, which later allows not only 3D but also 4D (over time) and 5D (including cost) simulation. As some research suggests there is still room for improvement as many smaller companies lag behind with implementing BIM in their processes and many find it too complex (Howard and Björk, 2008); and semantic interoperability between BIMs and in building information exchange between different applications from different disciplines continues to be a problem (Yang and Zhang, 2006). As this is a conceptual definition, the reality shows that there can be a wide range of possibilities in the 3D BIM approach, highly dependent on the way the participants of the project interact and how the BIM is used (Grilo and Jardim-Goncalves, 2010).

In the narrower field of oil and gas industry the international ISO15926 standard for information integration, handling and exchange between computer systems has been developed. The standard does not enforce the internal systems to be redesigned, nor proprietary data to be exposed to the outside systems. However once the systems implement the standard, computers should be able to exchange information without human intervention (Anon., 2008b). Having developed a generic data model and a reference library it turned out being able to model any state information (Wikipedia contributors, 2011a). However since it employs the theory of non-well-founded sets and is able to model non-terminating relationships (Aczel, 1988) the learning curve of such concept is very steep. It was debated (Smith, 2006) that a more familiar and simpler logic like Common Logic (Anon., 2008a) could be used to achieve similar results.

2.1.2 Knowledge sharing

Information integration and storage systems play critical role in the modern business and project management processes. They provide engineers with the information needed to perform actions ranging from day-to-day maintenance to critical situation management operations. Not all of the required information is stored in the information systems though; in fact most of it resides in the minds of the companies' employees (Nemati, et al 2002). The global population is ageing (more so in the industrialized countries) and because of the limited hiring and other factors it was predicted that a lot of the currently working engineers are due to retire in the next 10-15 years. A lot of the experience had been gathered at the time when there were no modern information systems. More intelligent systems and work processes are needed to allow and to encourage the employees to share the tacit information, store and convert it into explicit information, available for a new generation of engineers.

Not all information integration systems are suited for the knowledge management. Some companies are well known for their knowledge management practices. BP, for example, proved that helping to create communities of practice, introducing learning processes and creating environment where people are willing to share knowledge can be very beneficial (Edwards, 2007). It was also noted, that sometimes a simple tool (like a good search engine) can be more useful for the knowledge management than a complex one.

2.1.3 Web portals

Web portals present a convenient way of consolidating the information search mechanisms. Technologies are mature enough to deliver different types of content inside the browser – data, pictures, video clips, 2D and 3D models, documents, etc. It is common for the project contractor in the AEC sector to share information and responsibilities with the owner and subcontractors (Schramm, et al 2010), which may be located in different parts of the country or even different parts of the world. Portals can integrate information from such involved parties like designers, contractors, consultants, suppliers and make tracking of the information exchange possible for the managing bodies. Exposing these portal capabilities can be very valuable, as it reduces the information cycle times, allows teams to make quicker and more informed decisions (Samdani, 2007). What is also important that they provide a single point of access to the required information and this can lead to huge time savings (FIATECH, 2009).

Since most computers on the web have at least one browser installed, having a globally accessible information portal eliminates quite a lot of deployment and maintenance issues. Content available on the web portals is also mostly platform independent (with the exception of utilizing Microsoft ActiveX technology). This is very useful with the appearance of powerful mobile computing devices as more and more devices can be deliver the rich information content over the web. Some of the older enterprise web portals designed for the old Microsoft Internet Explorer (IE) 6 browser and those utilizing ActiveX technology will have difficulties reaching all of intended users and will have to be redesigned. However IE browser usage is constantly declining (Anon., 2011i) and newer versions of IE have a lot better support for W3C standards. It is only a matter of time when web pages will be able to fully utilize the rich features enabled by the HTML5 standard both on the personal and enterprise level.

2.2 Web 3D

Up until a few years ago there was no native way to render 3D content on the web. One of the possible ways to display a 3D model inside a web browser was to use a plug-in, which did the graphics rendering and was able to utilize the GPU resources. There are obvious issues when using browser plug-ins. They introduce additional maintenance issues; as browser and plug-in development cycles are different it may be difficult to maintain compatibility with all of the required browsers and operating systems. But probably the most important thing is that they create a separate virtual environment within a browser, isolate the DOM tree, events and CSS features. While it is possible to control the 3D model with the API and the event system provided by the plug-in, the developer is forced to learn the new framework and is dependent on the features provided.

The second way was to use 2D pipeline to give the user an impression a 3D model was being drawn. This approach has obvious performance issues. While current CPUs are quite powerful, it would still be impossible to render a 3D model comprising of a large number vertexes with an appropriate refresh rate. With the current generation of tablets and smart-phones already containing a separate GPU unit, the future looks bright for the web applications able to utilize the potential of the graphics engine.

This paper does not intend to provide a comprehensive review of the past and current Web3D technologies as these are covered in multiple papers already (Wright and Madey, 2008, Behr, et al 2010, Paulis, 2010, Ortiz Jr., 2010, etc), instead we focus on the more popular approaches that we believe have momentum, or could have some impact in the engineering sector.

2.2.1 VRML/X3D

VRML language is likely the first technology to allow 3D content on the web in 1994. It is a text based file format for defining 3D polygons in scene graph, along with their color, textures and lighting effects and featured its own event system. The technology required browser plugins and was often regarded too slow for the complex and large models. Some say it appeared too early for computers and software to support the graphics it enabled (Ortiz Jr., 2010), as one needs to take into account the speed of available CPUs and Internet connections of the time. Some research was done utilizing VRML as a mean to deliver 3D content to the web (Buriol and Scheer, 2008).

In 2007 VRML was superseded by the X3D standard. It is now based on XML markup language, new features for humanoid animation, lighting and texture rendering were added, and it also enhanced the programming interfaces. However the new standard has some of the same issues as it still requires plugins to display 3D content inside a browser and it defines a separate event system. It has separate profiles (one being CADInterchange) exposing different functionality, so developers can choose which features they wish to support.

2.2.2 JAVA3D, JOGL

Java3D is a high level language concept using VRML/X3D scene graph model and developed by Sun. Technology enables utilizing the GPU resources by using either Open GL or DirectX API. Not being part of the Java runtime environment, it requires additional Java 3D runtime environment to execute. It never achieved mass user adoption and Sun dropped the support of the framework in 2008 and is now supporting a low level programming interface called JOGL able to bind to the OpenGL API. Some research has been done using Java3D (Tay and Roy, 2003) and even more tying together VRML/X3D and Java3D (Li, et al 2004, Walsh, 2003, Kováč) as this enabled web applications to access desired GPU resources.

2.2.3 ActiveX

ActiveX is a Microsoft technology for defining a framework for creating Component Object Model (COM) based user controls. The controls are language independent and have access to various computer resources – GPU, disk file system, networking and others, otherwise inaccessible by the browser and can provide functionality like displaying certain file contents, animations or gather data. Since control definitions are embedded in the HTML code, a user viewing such page, is presented with an opportunity to download and run the control in the browser. This behavior has led to many security concerns in the past and was extensively utilized by malware. Though effort has been made to implement the ActiveX functionality in Firefox, it remains a Microsoft-specific technology. Some projects like VectorDraw are still running (Anon., 2011j) and some commercial software implement ActiveX components, however if a web portal seeks to target a wider range of operating systems and devices, this does seem to be an attractive solution.

2.2.4 Flash, Shockwave

Flash and Shockwave are Adobe frameworks to deliver rich media content to the web. Both of them are plugin based technologies, though they differ in implementation. Shockwave has full 3D GPU support and is extensible through the use of Xtras. Adobe Director is the only content creation tool that is able to produce Shockwave (.dcr) files. Flash had multiple authoring tools available and it got popular very quickly. Today it is believed to be installed on the absolute majority of the computers on the web delivering videos, sound and animation to the browsers. Flash got 3D hardware acceleration with the version 10, and the new API now supports features like cubic textures, z-buffering, fragment and vertex shaders, etc. Multiple projects have spawned using the Flash API like PaperVision3D (using 2D Flash API) (Anon., 2010) and later PaperVisionX (using 3D API), however development seems to have stopped and it is not clear what is the future of the project. There are now other Flash 3D engine projects like Away3D (Anon., 2011a), so this space is still worthwhile to look after.

2.2.5 WPF and Silverlight

These are Microsoft frameworks for creating rich internet applications, delivering animation, vector graphics, video and sound and targeting similar user base as the Flash technology. Employing XAML (a version of XML) to define links between its elements it utilizes Direct3D to display content so it also has access to the GPU resources. Silverlight is built on top of WPF and sharing the same presentation layer focuses more on visualization and user controls. The 5th version of Silverlight, which is now in beta (Anon., 2011h), exposes both 3D (based on XNA) and 2D APIs with DirectX/Direct3D support. This, however, seems to eliminate the immediate possibility to utilize the 3D API on non-Microsoft operating systems (MacOS, Linux, Android, etc).

2.2.6 WebGL

Started as a Mozilla project to create a JavaScript wrapper library for the OpenGL it is now becoming a major player in the Web3D arena developed by the Khronos Group, which released the first WebGL specification in 2011 (Anon., 2011k). Conforming to the HTML5 standards, it utilizes the Canvas element to render the 3D content inside the browser window. New versions of Mozilla's Firefox, Google's Chrome and development versions of Apple's Safari and Opera browsers support the WebGL natively. This is a huge bonus to the web developers as it means that the majority of browsers on the web will soon be able to render 3D content without any plugins needed.

There are several issues in WebGL implementation as well. Since it is a JavaScript based library, it heavily depends on the features and execution speed that the language provides. However with JavaScript performance increasing with each browser engine generation, the speed is only expected to increase. It is also a low level library, so requires quite a bit of knowledge about vertexes, transformations, shaders; this implies a higher level of complexity while of course allowing a higher degree of control. Also recently an independent security company published a report (Farshaw., 2011) pointing out security issues present in the current WebGL implementation, which allows malicious code to be run and either make the machine unusable or put "users' data, privacy and security at risk".

Numerous libraries utilizing WebGL are already available – SceneJS (Anon., 2011g) implements a scene graph, SpiderGL (Benedetto, et al 2011) allows developers to concentrate on the higher level objects, without forcing to comply with the scene graph paradigm or deal with the low level calls to the OpenGL API and many more similar approaches like C3GL(Anon., 2011b), GLGE (Anon., 2011c), etc.

2.2.7 Other approaches

Custom approaches merging several of the mentioned frameworks must also be mentioned. It seems that research mostly focuses around integrating VRML/X3D with other technologies. With Java3D already mentioned, a DWeb3D framework implementing collaboration, interaction with other applications and persistence was proposed (Quintella, et al 2010) to ease the development of applications by linking X3D model with the Unity3D engine.

Probably the most promising technologies are those which try to integrate X3D structure into the browser's DOM tree. Considering that quite a few authoring and design programs for creating engineering 3D content utilize scene graphs in their data formats, and that DOM tree itself is a single-parent graph, it only seems natural to be able to easily transfer and arrange the 3D objects inside the XHTML code. X3DOM implementation "acts as a connector for the HTML5 and X3D world and content" (Behr, et al 2010). It suggests a new X3D profile, implementing only the features required by the X3DOM model and isolating others. This and further work (Jung, et al 2011) allows the 3D content to be delivered to any X3D enabled browsers (supporting it either natively, by means of an X3D plugin, or falling back to WebGL library or Flash plugin) on multiple platforms.

XML3D project (Sons, et al 2010b) goes even further, as it strips even more functionality from X3D and tries to utilize the visualization and scripting components already provided by the CSS and DOM events. It offers two implementations – one WebGL and JavaScript implementation is more limited as "DOM scripting does not currently provide access to all CSS properties of an element or the possibility to attach event listeners to style changes", rendering is limited to the "hardware-accelerated rasterization" and while being quite fast it suffers from JavaScript performance updating the DOM tree. A native implementation embedded directly into the Mozilla and WebKit browser frameworks offers more features like faster DOM tree update, storing large 3D data arrays in the GPU using OpenGL VertexBufferObjects and utilizing the AnySL shading framework to be independent of the shading language used. Both XML3D and X3DOM projects look promising and with the teams collaborating on the topic (Sons, 2010a) this could lead to another useful standard.

3. Proposed Solution

Our approach to the integrated model data management comes from the need to have a flexible, high performance and scalable information integration platform. It should be able to store and retrieve data efficiently, be easy to use and encourage engineers to share their knowledge and integrate 3D web technology to provide a 3D view into the model data through a web portal. Knowledge sharing and 3D view would act as additional dimensions to the information data set, enabling more complex scenarios for simulations, training, maintenance or shut down operations.

Traditionally a relational database management system (RDBMS) solution is used for the data storage; however relational databases do not necessarily need to be applied to every storage problem. While transactional, high value systems need atomicity to keep the data absolutely consistent, many databases deployed on the web only need to be eventually consistent. As our staging area database is not a final storage for the data, we can accept relaxed consistency constraints. What we want, however, is the ability to achieve high throughput for reading and writing operations, which brings us to another issue.

The easiest way to increase the RDBMS performance is to scale the platform vertically (by adding more resources to the server). This works well until a certain point, when exponential cost of adding more resources becomes evident and such solution becomes prohibitively expensive or reaches technological limits. Another way to scale is to add more servers to the system. Relational database systems that support such cluster based solutions traditionally have proven to be very costly and complex.

Additionally we have noticed that data storage implementing a RDBMS solution often becomes impractical for reporting if the data is highly normalized. To make reporting feasible either normalization constraints have to be relaxed or additional steps then have to be performed to denormalize the data like in (Brazhnik and Jones, 2007). In practice, while suitable for data warehousing solutions, it is not desired in operations, where people do not want to wait hours for huge data sets to be normalized and then denormalized again, just to see the incoming data had problems and has to be rejected. Thus this research project developed a platform that is designed for data cleansing and integration, enabling users to get insight into the data in the early stages of processing. The high level model of the proposed platform is shown in Figure 1:

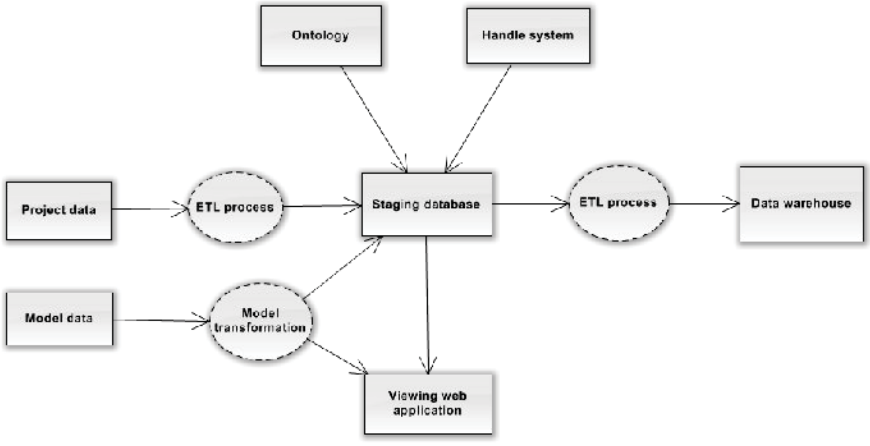

Fig. 1: Conceptual model for the integration platform.

ETL (Extract, transform, load) process will convert data from different formats into a format, that is suitable for the database import, or export data to another formats. Model transformation is needed to reduce the model size (by storing additional non-graphical information in the database) and to convert the model to a format suitable for displaying on the web. By applying the hybrid ontology approach as shown in Figure 2, it is possible to map single project vocabulary to local ontology used by the other designers or contractors.

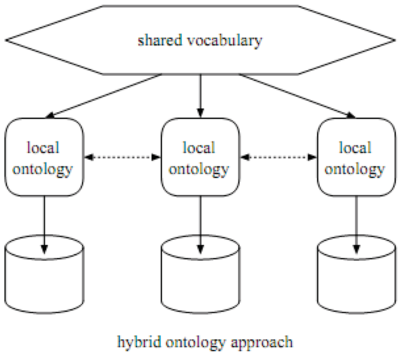

Fig. 2 (Wache, et al 2001): Mapping a single vocabulary to local ontology.

With the staging database in mind we believe that our system should provide a flexible schema definition, as we cannot predict all the attributes, functions and relations to be integrated. And the today's tendency is to move to the cloud-based solutions, thus we feel that the horizontal scaling should also be one of the key features of the proposed system.

After considering various RDBMS and NoSQL, sometimes also called structured storage (Wikipedia contributors, 2011b), solutions we focused our attention on document-oriented databases as these provide good support for semi-structured data storage, allowing more flexibility than relational databases and at the same time providing a data model that is more consistent with the our data or objects than a simple key-value store, which is more suitable for simplistic mapping approaches. One of the databases that seemed particularly appropriate was MongoDB (Anon., 2011e), as it is focused on performance but also has good availability and consistency features. We were able to achieve thousands of input/output operations per second (IOPS) even on commodity hardware and simple querying interface, which is a bit similar to SQL language, does not require map-reduce functions for basic queries and makes life for the developer a lot easier.

Handle system (Anon., 2011d) was chosen as a platform for the globally unique identifier system. It provides the whole framework for storing, resolving and retrieving the identifiers along with the metadata, which can be used to store links and identifiers to other systems. The distributed nature of the system means that we are responsible for storing the handles for our domain (we are assigned a certain prefix), thus can employ any data storage mechanism we see fit. But at the same time they are globally resolvable from any site or system capable of such function.

WebGL seems to be emerging as one of the core technologies for displaying 3D content as more and more browsers are natively supporting it. It may not be the fastest method of displaying 3D content in the browser, but it supports GPU acceleration and combined with the HTML 5 standard it offers rich development capabilities. Coupled with X3D scene graph mechanism it looks to be well aligned at least with some of the 3D authoring tools like 3ds Max or AutoCAD. As our ultimate goal is to have a 3D model inside a browser page, preferably without any plug-ins, tying closely to the DOM tree, utilizing CSS standards for styling 3D objects and browser event system for interaction and manipulation, the basic XML3D approach seems to be one of the better candidates for the job. We will keep an eye for the future development in the area as the collaboration of XML3D and X3DOM teams may bring something new. Ultimately, if this technology is to be pursued, browser developers may have to implement some of the X3D functionality to achieve peak 3D performance, however in the foreseeable future it does not seem likely.

4. Discussion and Further Work

Since the project is in early stages of research only the basic functions of the integration platform have been implemented and tested. More work will be needed for developing means of managing the platform as a service by using cloud deployment and management resources.

One of the major hurdles predicted will be the HTML file size as the 3D models grow and are incorporated into the DOM tree and the time to transfer the model over the network may become substantial. While X3D supports subtrees we will also be looking into ways of splitting the 3D model into separate equipment models, storing them in a database for efficient storage and retrieval. If the model can be split into separate files and efficiently reassembled at the client side, the separate pieces could be cached separately by the browser. Thus a small change in the model would not force the reload of the whole DOM tree from the server. Even upon closing and reopening the browser, parts of the model could be retrieved from the cache and would not have to be retransmitted over the network. More research will have to be done to determine whether this is a feasible solution.

How well the XML3D approach is going to cope with the large 3D models available in construction is another open question. JavaScript engines used in the browsers are still planned to improve so overall performance is very likely to increase with each browser generation. With Java3D not being supported anymore, Adobe Flash and Microsoft Silverlight frameworks are also able to efficiently tap into the GPU resources. Both lack the standardized way for constructing and displaying the 3D model in a scene graph or other manageable structure and we feel are more suited to creating new content than importing existing engineering model designs.

5. Conclusions

We have chosen a set of technologies that offer a path to achieve our goal of displaying 3D engineering content on the web. We've chosen a document-oriented database system and started implementing a staging database concept, coupled with a universally unique and resolvable digital object identifier framework. The research already done in the area shows potential for achieving our goal by utilizing XML3D approach. More research and development will be done in the near future to look into the outstanding issues and try to find efficient solutions to them.

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MEASUREMENT PLANNING OF THREE-DIMENSIONAL SHAPE BY MATHEMATICAL PROGRAMMING

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ABSTRACT: *A 3D scanner is a surface imaging system which is based on accurate distance measurement by electro-optical distance measurement. We can obtain the surface data of measurement objects by performing a number of independent measurements, and a 3D image emerges by merging them. In this paper, we assume that measurement objects are comparatively large, for example, terrain surfaces and constructions. One of the most difficult problems in collecting the complete surface data of measurement objects is to avoid occlusions. To collect the complete data, we usually have to measure the objects from multiple viewpoints. However, examining multiple surface visibilities relative to variable multiple viewpoints is a complicated problem. Hence, making an effective measurement plan a priori to avoid redundancy in both labor and computational costs is quite important. For this problem, the authors have proposed a method for making a measurement plan by using a ground plan of a target area (Dan et al. 2010). This method generates an optimized initial view plan beforehand using mathematical programming. However, this method is based on a 2D plan and hence, it is useful only for the cases where the height differences of the objects are not important comparatively. In this paper, we propose a method for making an effective plan to measure the 3D shape of outdoor objects by a 3D scanner. In our purposed method, we calculate visibility and the amount of obtainable data on the objects by considering their 3D shape. Also, we use the mathematical programming to find the least number of measurements needed to measure all the surfaces of the objects and determine viewpoints to maximize the sum of the amount of scanned data within the limitation of the number of measurements. The numerical experiments show that the proposed method works well for practical settings.*

KEYWORDS: *3D Scanner, Three-Dimensional Shape, Mathematical Programming, View Planning.*

1. Introduction

A 3D scanner is a surface imaging system which is based on accurate distance measurement by electro-optical distance measurement. We can obtain the surface data of measurement objects by performing a number of independent measurements, and a 3D image emerges by merging them. In this paper, we assume that measurement objects such as terrain surfaces and construction, for example, are comparatively large. One of the most difficult problems for collecting the complete surface data of measurement objects is to avoid occlusions. To collect the complete data, we usually have to measure the objects from multiple viewpoints. However, examining multiple surface visibilities relative to variable multiple viewpoints is a complicated problem. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. Hence, making an effective measurement plan *a priori* to avoid redundancy for both labor and computational costs is quite important.

View planning with a laser scanner has been developed as a trial-based scheme, which shows scanned segments and unscanned regions in a target scene to find the next best scanning viewpoint to minimize the unscanned regions. This approach includes methods for promoting the efficiency of sequential scanning (Asai et al. 2007, Pitto 1999, Pulli 1999) and a three-dimensional environmental map generation by autonomous mobile robots (Blaer and Allen 2009, Grabowski et al., 2003, Surmann et al., 2003).

For this problem, the authors have proposed a method for making a measurement plan by using the ground plan of a target area (Dan et al., 2010). This method generates an optimized initial view plan beforehand by using mathematical programming. Before starting the scanning process, estimating the minimum scale and the complexity of the whole scanning task is important and useful, especially for large-scale outdoor measurements. However, this method is based on a 2D plan, and hence, it is useful only for the cases where the height differences of the objects are not important comparatively. Moreover, 3D scanning is often required for elaborate examinations including flood simulations, for example, since even aerial surveys do not always provide sufficient resolution and accuracy to acquire detailed terrain data for a large area.

Therefore, in this paper, we propose a method for making an effective plan to measure the 3D shape of outdoor objects by a 3D scanner. In our purposed method, we calculate visibility and the amount of obtainable data on the objects by considering their three-dimensional shape. Also, we use mathematical programming to find the least number of measurements needed to measure all the surfaces of the objects and to determine viewpoints to maximize the sum of the amount of scanned data within the limitation of the number of measurements.

This paper is organized as follows: In Section 2, we define the problems in this paper. In Section 3, we prepare mathematical programming models to find an optimal solution to those problems. In Section 4, we propose a method for calculating the parameters' values needed in the mathematical programming models. In Section 5, we show numerical results using our proposed method, and we make concluding remarks in Section 6.

2. Definition of Our Problems

In this section, we introduce the definition of the problems in this paper, which are almost the same as those of the previous research (Dan et al., 2010). However, we explain them here again for the completeness of this paper.

We use a 3D scanner to measure the shape of measurement objects in the target area. A 3D scanner performs a line search vertically, and turns itself 360 degrees horizontally. In this way, the scanner can measure objects omni-directionally.

The goal of this research is to determine the viewpoints from which we can measure all the surfaces of measurement objects and we measure the surfaces from multiple points of view. As briefly discussed in Section 1, a view plan deeply depends on the shapes of structures, self and mutual occlusions, and the existence of obstacles. The visibility and occluding property of surfaces vary with the change of viewpoints nonlinearly and discontinuously, so determining the least number of viewpoints to measure all the surfaces is difficult.

Accordingly, we define one of the problems dealt with in this paper as follows:

[Problem 1] How many viewpoints do we need to measure all the surfaces of measurement objects in the target area?

Too few viewpoints may cause a deterioration in the quality of measurement. Therefore, we want to maximize the amount of data under the limitation of the number of measurements.

From this fact, we must consider the following problem:

[Problem 2] How we can determine an optimal layout of viewpoints to maximize the amount of scanned data under the limitation of the number of measurements?

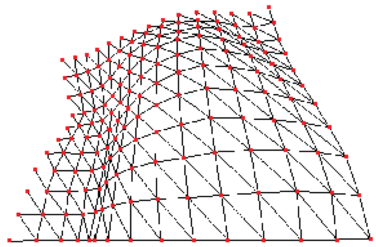

Fig. 1: Triangulation of natural terrain

In this paper, we propose a method for solving Problems 1 and 2 using mathematical programming.

In this research, we approximate the surfaces of measurement objects by triangles (Figure 1). The definition of this triangulation will be explained in Section 4. Moreover, we suppose that candidate points for measurement are placed in the target area beforehand.

3. Mathematical Programming Models

In this section, we formulate Problems 1 and 2 as 0-1 integer programming problems. As discussed above, these models have been proposed in the previous research (Dan et al., 2010). We use the same model in this paper.

We will use the following symbols in the mathematical programming models in this paper:

[Sets and Indexes]

- $i \in I$: candidate points for measurement,
- $j \in J$: triangles on the surfaces of measurement objects.

[Variables]

$$x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint,} \\ 1, & \text{a candidate point } i \text{ is adopted as a viewpoint.} \end{cases}$$

[Parameters]

$$d_{ij} := \begin{cases} 0, & \text{a triangle } j \text{ is unmeasurable from a candidate point } i, \\ 1, & \text{a triangle } j \text{ is measurable from a candidate point } i, \end{cases}$$

$$a_{ij} := \begin{cases} 0, & d_{ij} = 0, \\ \text{the amount of scanned data on a triangle } j \text{ from a candidate point } i, & d_{ij} = 1, \end{cases}$$

$r :=$ the upper bound of the number of measurement.

We calculate the value of parameters from 3D information on the target area. The calculation method will be introduced in Section 4.

In this paper, we use these two mathematical programming models (Dan et al, 2010):

$$\begin{aligned} &\text{minimize} && \sum_{i\in I} x_i \\ &\text{subject to} && \sum_{i\in I} d_{ij}x_i \geq 1 \quad (\forall j \in J), \\ &&& x_i \in \{0,1\}. \end{aligned} \tag{1}$$

$$\begin{aligned} &\text{maximize} && \sum_{i\in I, j\in J} a_{ij}x_i \\ &\text{subject to} && \sum_{i\in I} d_{ij}x_i \geq 1 \quad (\forall j \in J), \\ &&& \sum_{i\in I} x_i \leq r, \\ &&& x_i \in \{0,1\} \quad (\forall i \in I). \end{aligned} \tag{2}$$

The objective function of (1) is to minimize the number of viewpoints. Also, the term in the first constraint of (1) means as follows:

$$d_{ij}x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint } (x_i = 0) \\ & \text{or a triangle } j \text{ is unmeasurable from } i \ (d_{ij} = 0), \\ 1, & \text{a candidate point } i \text{ is adopted as a viewpoint } (x_i = 1) \\ & \text{and a triangle } j \text{ is measurable from } i \ (d_{ij} = 1). \end{cases}$$

Therefore, the first constraint of (1) means that all the triangles should be measured from one viewpoint at least.

The term $a_{ij}x_i$ of the objective function of (2) means as follows:

$$a_{ij}x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint } (x_i = 0) \\ & \text{or a triangle } j \text{ is unmeasurable from } i \ (a_{ij} = 0), \\ a_{ij}, & \text{a candidate point } i \text{ is adopted as a viewpoint } (x_i = 1) \\ & \text{and a triangle } j \text{ is measurable from } i \ (a_{ij} > 0). \end{cases}$$

Therefore, the objective function of (2) is to maximize the sum of the amount of scanned data. In addition, the first and third constraints of (2) are the same as that of (1). Moreover, the second constraint of (2) is to restrict the number of measurements less than or equal to r.

As we see above, the mathematical programming problems (1) and (2) are the counterparts of Problems 1 and 2, respectively.

4. Calculation of Parameters' Values

In this section, we explain the method for calculating the parameters' values needed in the mathematical programming models (1) and (2).

4.1 Preliminaries

4.1.1 Orientation of Faces of Triangles

In this research, we assume that the two faces of triangles on the surfaces of measurement objects have an orientation. The orientation is determined by a sequence of three vertices. If the sequence of three vertices, P_1, P_2 and P_3, is anticlockwise on a face, then the face is the positive side (Figure 2, left). Otherwise, the face is the negative side (Figure 2, right). Also, we can judge whether a face is positive or negative by using the cross product (Figure 3). It is well known that the cross product $(P_2 - P_1) \times (P_3 - P_1)$ is a normal vector of the plane which includes P_1, P_2 and P_3. In this case, the normal vector by the cross product emerges in the half space of the positive side of the triangle $\Delta P_1P_2P_3$.

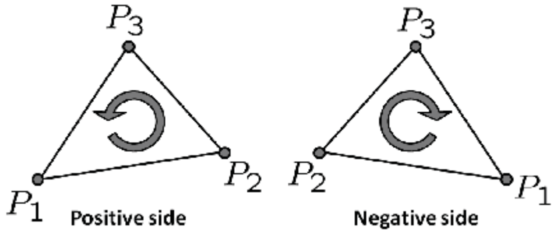

Fig. 2: Orientation of faces of triangles (left: positive side, right: negative side)

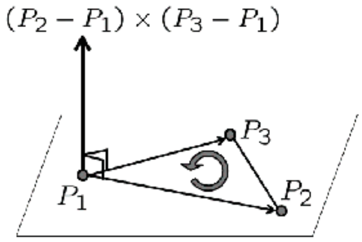

Fig. 3: Judgment of orientation of triangles by the cross product

In this research, we assume that we have to measure the positive side of each triangle.

4.1.2 The Signed Area of Triangles and an Intersection Test for Two Line Segments in 2D

First, we define the signed area of triangles in 2D. We can calculate the signed area of a triangle by

$$S(\Delta P_1P_2P_3) = \frac{1}{2}((x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1)),$$

where the three vertices of the triangle are $P_1(x_1, y_1), P_2(x_2, y_2)$ and $P_3(x_3, y_3)$. Note that this value could be negative. If it is positive, then the sequence P_1, P_2 and P_3 is anticlockwise, that is, $\Delta P_1P_2P_3$ is positive. In other words, P_3 is on the left side of vector $\overrightarrow{P_1P_2}$. If it is negative, then the sequence P_1, P_2 and P_3 is clockwise, that is, $\Delta P_1P_2P_3$ is negative. Also, if it is zero, then P_1, P_2 and P_3 are collinear.

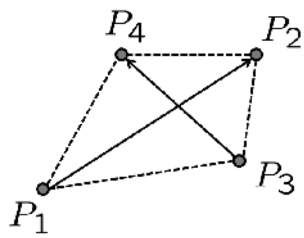

Fig. 4: An intersection test for two line segments

Moreover, by using the signed area of triangles, we can judge whether two line segments in 2D intersect or not. For the two line segments, P_1P_2 and P_3P_4, the conditions

$$S(\Delta P_1P_2P_3) \cdot S(\Delta P_1P_2P_4) < 0 \text{ and } S(\Delta P_3P_4P_1) \cdot S(\Delta P_3P_4P_2) < 0$$

hold if and only if the two line segments intersect.

4.1.3 An Intersection Test for a Triangle and a Ray in 3D

In this section, we explain a method for judging whether the triangle ΔOAB and the ray vector $\overrightarrow{PQ}$ in 3D intersect or not (Figure 5).

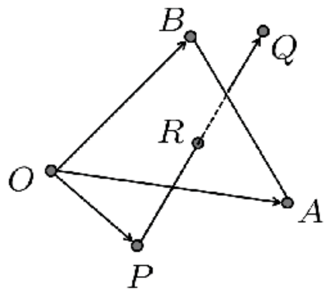

Fig. 5: An intersection test for a triangle and a ray

A point R denotes the point where the ray $\overrightarrow{PQ}$ and the plane including ΔOAB intersect. We can express R by $s\overrightarrow{OA}+t\overrightarrow{OB}$, where s and t are scalars. In addition, we can also express R by $\overrightarrow{OP}+u\overrightarrow{PQ}$, where u is a scalar. Thus, we obtain the linear equations

$$s\overrightarrow{OA}+t\overrightarrow{OB}=\overrightarrow{OP}+u\overrightarrow{PQ} \Leftrightarrow \begin{bmatrix}\overrightarrow{OA} & \overrightarrow{OB} & \overrightarrow{OP}-\overrightarrow{OQ}\end{bmatrix}\begin{bmatrix}s\\ t\\ u\end{bmatrix}=\overrightarrow{OP}.$$

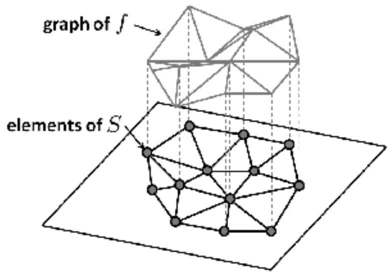

Fig. 6: Definition of triangulation

For the solution of this system of linear equations, the conditions $s>0, t>0$ and $s+t<1$ hold if and only if R lies in the inside of ΔOAB, that is, ΔOAB and $\overrightarrow{PQ}$ intersect.

4.1.4 Definition of Triangulation

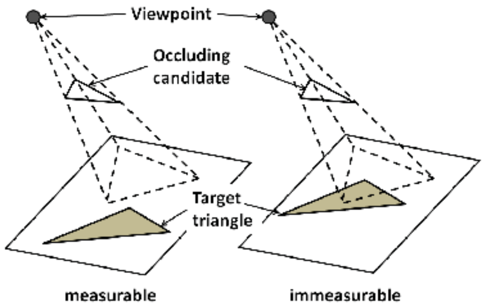

Fig. 7: Visibility of a target triangle

As mentioned in Section 2, we assume that the surfaces of measurement objects are approximated by triangles (ex. Figure 1). For simplicity, we assume that all the triangles should be measured. However, we can apply the method in this paper to the case where a subset of the triangles would be measured.

The definition of this triangulation is as follows: the surfaces of measurement objects are considered as the graph of a function $f:\Re^2\to\Re$. Note that we do not know the values of the function at all the points in the domain, that is, the heights of all the points in the measurement region are not known. A set of finite points whose heights are known is denoted S. Under this setting, the convex hull of S is divided by triangles. If all the vertices of the triangles are the points of S, then we call it a triangulation of S (Figure 6).

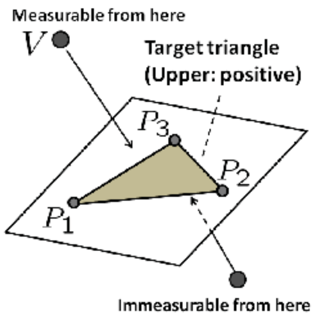

Fig. 8: Relationship between a viewpoint and a triangle

There are various methods for making a triangulation. One of the most typical methods is Delaunay triangulations (Section 9, de Berg et al., 2008). Delaunay triangulations maximize the minimum angle over all the triangulations of S (Theorem 9.9, de Berg et al., 2008). Intuitively, this means that Delaunay triangulations avoid thinner triangles, and this avoidance is a desirable property for good approximation of surfaces.

4.2 Visibility Test

From the definition of the triangulation in Section 4.1.4, we can suppose that triangles, which approximate the surfaces of measurement objects, do not intersect each other and no two of them share three vertices;

that is, no two triangles are identical. Also, we assume that a target triangle is measurable from a viewpoint when the whole of the triangles can be scanned from the viewpoint (Figure 7).

For our goal, we have to examine the visibility, that is, whether a triangle can be measured from a viewpoint or not.

In the following, we explain a method for judging whether the triangle $\Delta Q_1Q_2Q_3$ occludes the target triangle $\Delta P_1P_2P_3$ or not when the measurement is conducted from viewpoint V.

First, we check whether viewpoint V lies in the positive side of the target triangle $\Delta P_1P_2P_3$ or not (Figure 8). As we saw in Section 4.1.1, the normal vector of $\Delta P_1P_2P_3$ by the cross product lies in the positive half space (Figure 3). Therefore, we can judge whether V lies in the positive half space or not by the value $\langle (P_2 - P_1)\times(P_3 - P_1), V - P_1 \rangle$, where $\langle \bullet, \bullet \rangle$ is the inner product. If it is positive, then V lies in the positive half space. If V lies in the positive side, then we have to examine whether the other triangles occlude it or not. Otherwise, the triangle cannot be scanned from the viewpoint.

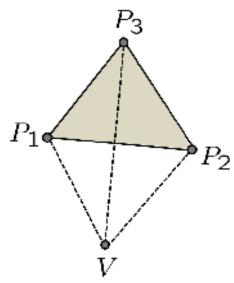

Fig. 9:The triangular pyramid generated by a viewpoint and a target triangle

Next, we will check the occluding property of $\Delta P_1P_2P_3$ by $\Delta Q_1Q_2Q_3$ scanning from V. We classify the relationship between P and Q as follows:

- (i) No vertex is shared by P and Q
- (ii) One vertex is shared by P and Q
- (iii) Two vertices are shared (= one edge is shared) by P and Q

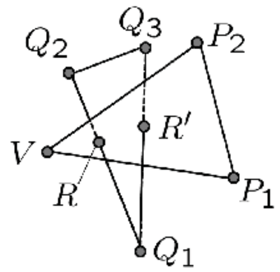

Fig. 10: The intersection test for (i)-(1)

We explain the method for judging the occluding property for these cases in the following subsections.

4.2.1. Visibility Test for the Case (i)

In this case, $\Delta Q_1Q_2Q_3$ does not occlude $\Delta P_1P_2P_3$ when $\Delta Q_1Q_2Q_3$ does not intersect the triangular pyramid $V - P_1P_2P_3$ (Figure 9). From the definition of the triangulation, $\Delta Q_1Q_2Q_3$ does not intersect $\Delta P_1P_2P_3$. Thus, if $\Delta Q_1Q_2Q_3$ intersects $V - P_1P_2P_3$, then $\Delta Q_1Q_2Q_3$ intersects at least one of the three side faces, ΔVP_1P_2, ΔVP_2P_3 and/or ΔVP_3P_1. Therefore, we have to check whether $\Delta Q_1Q_2Q_3$ intersects the three side faces or not. In the following, we will explain the intersection test on $\Delta Q_1Q_2Q_3$ and ΔVP_1P_2 (Held, 1997). We can, of course, apply the test to ΔVP_2P_3 and ΔVP_3P_1.

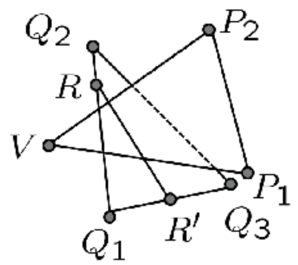

Fig. 11: The intersection test for (i)-(2)

First, we check whether Q_1, Q_2 and Q_3 lie in the positive half space of ΔVP_1P_2 or not. If Q_1, Q_2 and Q_3 lie in the same half space, then $\Delta Q_1Q_2Q_3$ does not intersect ΔVP_1P_2. In the other case, without loss of generality, we assume that Q_1 lies in the positive half space and Q_2 and Q_3 lie in the negative half space. R and R' denote the intersection points between the plane including ΔVP_1P_2 and the two line segments Q_1Q_2 and Q_1Q_3, respectively. R and R' can be calculated by the method in Section 4.1.3. If R and/or R' lie in the inside of ΔVP_1P_2, then $\Delta Q_1Q_2Q_3$ intersects ΔVP_1P_2 (Figure 10). Otherwise, we will check whether the line segment RR' inter-

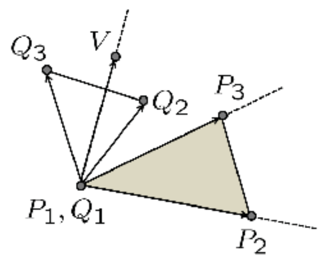

Fig. 12: The intersection test for (ii)-(1)

sects VP_1 and/or VP_2 or not (from the definition of the triangulation, RR' does not intersect P_1P_2). This intersection can be calculated by the method in Section 4.1.2. If RR' intersects VP_1 and/or VP_2, then $\Delta Q_1Q_2Q_3$ intersects ΔVP_1P_2 (Figure 11). Otherwise, $\Delta Q_1Q_2Q_3$ does not intersect ΔVP_1P_2.

4.2.4 Visibility Test for the Case (ii)

We assume that $P_1 = Q_1$ holds without loss of generality (Figure 12). In this case, we will solve the following system of linear equations:

$$\left[\overrightarrow{OP_2} - \overrightarrow{OP_1} \quad \overrightarrow{OP_3} - \overrightarrow{OP_1} \quad \overrightarrow{OV} - \overrightarrow{OP_1}\right]\begin{bmatrix} s_i \\ t_i \\ u_i \end{bmatrix} = \overrightarrow{OQ_i} - \overrightarrow{OQ_1} \quad (i = 2,3). \tag{3}$$

We understand that (3) is the transformation of axes whose origin is P_1 and whose bases are $\overrightarrow{P_1P_2}, \overrightarrow{P_1P_3}$ and $\overrightarrow{P_1V}$. The transformed points are denoted $\bar{\bullet}$ (Figure 13).

If $(s_2,t_2,u_2) > (0,0,0)$ and/or $(s_3,t_3,u_3) > (0,0,0)$ hold, then $\Delta Q_1Q_2Q_3$ occludes $\Delta P_1P_2P_3$ when $\Delta P_1P_2P_3$ is measured from V because the line segment $\overline{Q_1}\,\overline{Q_2}$ and/or $\overline{Q_1}\,\overline{Q_3}$ intersects the triangular pyramid $\overline{V} - \overline{P_1}\,\overline{P_2}\,\overline{P_3}$. In the other case, we will check whether the line segment $\overline{Q_2}\,\overline{Q_3}$ intersects $\{(s,t,u) \mid s = 0, t \geq 0, u \geq 0\}$ and/or $\{(s,t,u) \mid s \geq 0, t = 0, u \geq 0\}$. It can be checked easily because the conditions are very simple. Note that $\overline{Q_2}\,\overline{Q_3}$ does not intersect $\{(s,t,u) \mid s \geq 0, t \geq 0, u = 0\}$ because of the assumptions. If $\overline{Q_2}\,\overline{Q_3}$ intersects at least one of them, then $\Delta Q_1Q_2Q_3$ occludes $\Delta P_1P_2P_3$. Otherwise, $\Delta Q_1Q_2Q_3$ does not occlude $\Delta P_1P_2P_3$.

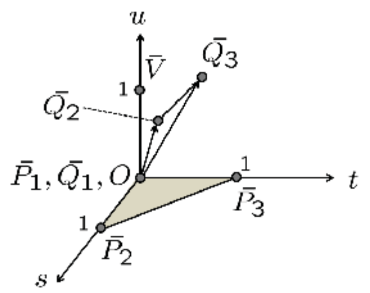

Fig. 13: Transformation of axes

4.2.3Visibility Test for the Case (iii)

We assume that $P_1 = Q_1$ and $P_2 = Q_2$ hold without loss of generality (Figure 14). In this case, we solve (3) for $i = 3$. If $t_3 > 0$ and $u_3 > 0$ holds, then $\Delta Q_1Q_2Q_3$ occludes $\Delta P_1P_2P_3$ when $\Delta P_1P_2P_3$ is measured from V. Otherwise, $\Delta Q_1Q_2Q_3$ does not occlude $\Delta P_1P_2P_3$.

4.2.4 All of the Visibility

In Section 4.2, we explained the method for judging whether a triangle occludes another triangle or not. Therefore, we can judge the whole visibility by applying this method to all combinations of all the triangles and the viewpoints (Figure 15). However, by some preprocessing, we can narrow the combinations which must be checked. For example, we can omit the case where $\max\{VP_1, VP_2, VP_3\} \leq \min\{VQ_1, VQ_2, VQ_3\}$ holds. Also, we can ignore the case where the angle range of $\Delta P_1P_2P_3$ from V does not overlap that of $\Delta Q_1Q_2Q_3$ (Figure 16).

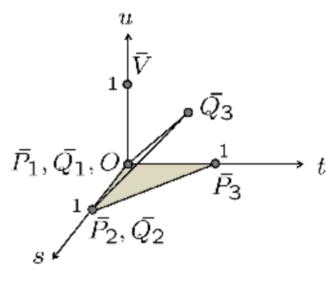

Fig. 14: The intersection test for (iii)

4.3 The Amount of Obtainable Data

For the case that $\Delta P_1P_2P_3$ is measurable from V, we have to calculate the amount of data which would be obtained by a 3D scanner. From the principle of a 3D scanner, the amount of data is proportionate to the solid angle of $\Delta P_1P_2P_3$ from V. A solid angle of $\Delta P_1P_2P_3$ from V is defined to be the area of the intersection of the cone generated by V and $\Delta P_1P_2P_3$ and a sphere of unit radius (Figure 17).

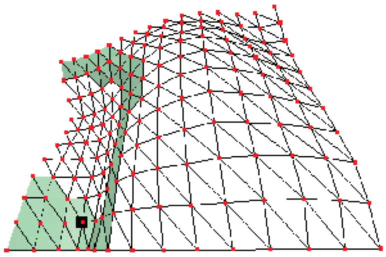

Fig. 15: Result of visibility test

It is known that the solid angle of $\Delta P_1P_2P_3$ from V can be obtained by

$$s = \theta_1 + \theta_2 + \theta_3 - \pi,$$

where $\theta_i (i = 1,2,3)$ are the three angles between three side faces of the triangular pyramid $V - P_1P_2P_3$ (Figure 17).

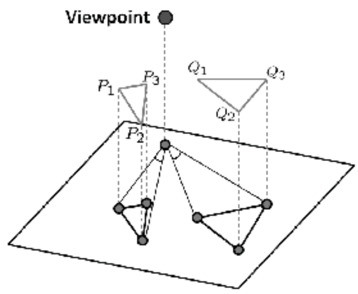

Fig. 16: Example of an omissible case

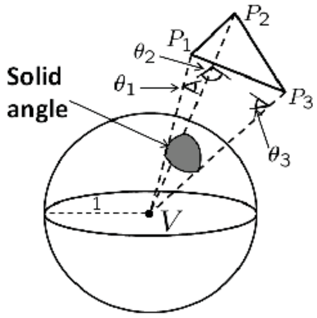

Fig. 17: The solid angle

5. Numerical Results

In this section, we report numerical results using the proposed method in this paper.

Table 1: The number of vertices and triangles

	Vertex	Triangle
Example 1	165	280
Example 2	869	1539

Table 2: Experimental environment

PC	Lenovo ThinkPad X200s
OS	Windows XP Professional SP3
CPU	Intel Core2 Duo L9300 @ 1.60GHz
Memory	2.96GB
Solver	GLPK LP/MIP Solver version 4.43

We have applied the proposed method to two examples of the natural terrain. Example 1 is Figure 1 (page 2), and Example 2 is Figure 18. The target of Examples 1 and 2 are about 100 m× 100m and 1000m × 1000m areas of Hozu-kyou (Kyoto, Japan). These areas have many up and down hills. Thus, they seem appropriate

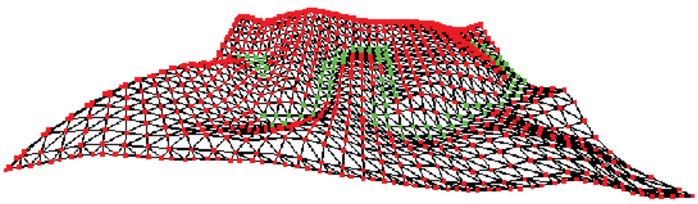

Fig. 18: Example 2

for measurement-planning experiments. The raw terrain data of these areas has been derived from Google Earth, and we have processed it by Google SketchUp.

We have set vertices and triangles to approximate the surfaces in these areas. Table 1 shows the number of vertices and triangles for Examples 1 and 2. Also, we have set candidate viewpoints for these examples. The candidate points are about 2m above all the vertices. Thus, the number of candidate points is equal to the number of vertices in each example.

We have employed the experimental environment in Table 2 to solve (1) and (2), and we have obtained the optimal viewpoints as Figures 19 and 20. Table 3 shows the computational time and the least number of measurements to scan all the triangles. In these experiments, we have set the value of r in (2) as the optimal value of (1).

Table 3: Computational time and the least number of measurements

	Example 1	Example 2
Computational time to solve (1) (sec.)	<0.1	6.2
The least number of measurements by (1)	13	13
Computational time to solve (2) (sec.)	0.2	6.6

In these experiments, we have set $d_{ij} = 1$ as long as a solid angle from a candidate point i to a triangle j is even a little bit larger than 0. However, sometimes we want to judge that a wall is immeasurable when a solid angle is too small. To consider such a situation, we have conducted some experiments on Example 2, in which we have set $d_{ij} = 0$ and $a_{ij} = 0$ if a solid angle is less than a threshold of the minimal solid angle.

Table 4: Minimal solid angle and the least number of measurements

Minimal Solid Angle (sr)	$4\pi/10000$	$4\pi/1000$
Computational time to solve (1) (sec.)	2.0	66.3
The least number of measurements	45	133
Computational time to solve (2) (sec.)	5.8	614.4

Table 4 shows the relationship between the minimal solid angle and the least number of measurements, and the optimal viewpoints are depicted in Figures 21 and 22. The complete solid angle is 4π steradians (= the surface area of a sphere with unit radius). Thus, the minimal solid angles $4\pi/10000$ and $4\pi/1000$ are 0.01% and 0.1% of the complete solid angle, respectively.

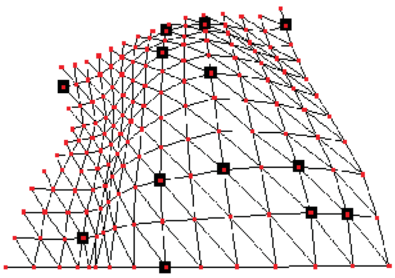

Fig. 19: Optimal Viewpoints (Example 1)

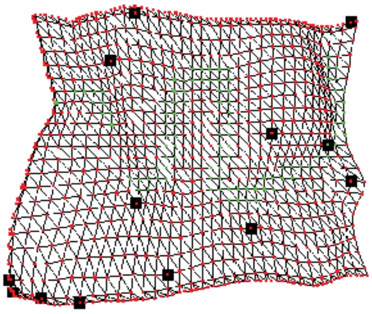

Fig. 20: Optimal Viewpoints (Example 2)

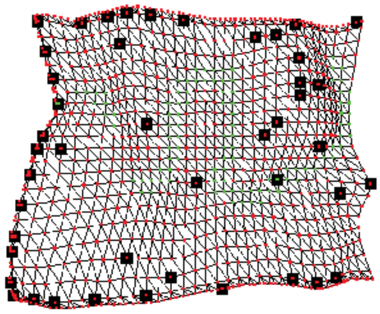

Fig. 21: Optimal Viewpoints (Minimal solid angle: 4π */10000)*

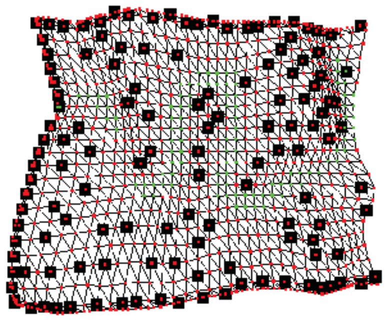

Fig. 22: Optimal Viewpoints (Minimal solid angle: 4π */1000)*

The obtained results show that our method is sufficiently applicable to practical settings.

6. Conclusion

In this paper, we have proposed a method for finding an optimal view-plan to scan all the surfaces of measurement objects by a 3D scanner. To simplify our problems, we assume that surfaces of measurement objects are approximated by triangles. One of the most difficult problems is to avoid occlusions. For this purpose, we examine occluding properties between a target triangle and the other triangles by some geometrical calculation.

Our previous research (Dan et al., 2010) has dealt with almost the same problems as that of this paper. However, it depends on a 2D diagram deeply. On the other hand, the proposed method in this paper can handle 3D data on the target region. Thus, this research overcomes the disadvantage of the previous research.

Acknowledgments

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ON DECISION-MAKING AND TECHNOLOGY-IMPLEMENTING FACTORS FOR BIM ADOPTION

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ABSTRACT: *While many existing studies on Building Information Modeling (BIM) have focused on technological interoperability, only a few have been dedicated to studying the impacts of adopting BIM technology on business processes. These few studies have found that the adoption of BIM technology has been slow due to poor understanding of the mechanism of the evolution of BIM adoption and the lack of effective assessment of the evolution of BIM adoption in the organization. To address this shortcoming, this research explores and develops a technique to assess the evolution of BIM technology adoption among architecture, engineering, and construction (AEC) companies in Taiwan. This research represents first steps towards identifying, compiling, and validating decision-making and technology-implementing factors (DMTIFs) for BIM technology adoption. This paper presents an overview and literature review on decision-making and technology-implementing factors considered significant in influencing BIM adoption. This study adopts the paradigm shift perspective of BIM implementation in the form of four BIM adoption stages that delineate implementation maturity levels of BIM: visualization, coordination, adaptation, and integration. In each stage, six areas of interest are categorized: organizations, applications, tools, project teams, processes, and business models. We present the main features of our research methodology that include questionnaire surveys, interviews, and case-studies. The survey results are expected to enable the development of a weighted BIM Decision-Making and Technology-Implementing Index (BIM DMTII) and provide further understanding of what the most critical decision-making and technology-implementing factors are. They also serve as a foundation for further case studies to obtain deeper insights into the effectiveness of BIM DMTIFs in assisting the BIM users or organizations for decision-making and the implementation of BIM adoption in practice.*

KEYWORDS: *Building Information Modeling (BIM), BIM Technology Adoption, BIM Decision-Making and Technology-Implementing Index (BIM DMTII), AEC Industry*

1. Introduction

Over the past forty years, productivity in the construction industry has declined significantly due to many factors. The adoption of information technology practices in the industry is one of them (Teicholz 2004).With modern visualization technology that centers around virtual reality (VR), augmented reality (AR), and mixed reality (MR), the two-way communication (mapping) of information between the real world (physical objects with attributes) and the virtual world (corresponding digital models with real world data) in full-scale and real-time (Whyte et al. 2000; Woodward et al. 2010; Xie et al. 2011;Yeh et al, 2011) can be established and managed in a more direct way than ever. This has also facilitated great improvements in the control and monitoring of onsite construction processes, the operation and maintenance of facilities, and design processes in the office. Building information modeling (BIM) is the process of creating and managing parametric digital models of a building (or an infrastructure) during the building's lifecycle (Eastman et al. 2008). BIM has been perceived by both academia and the industry as a new approach that can improve productivity and quality in the construction industry (Smith and Tardif 2009). However, the adoption of BIM technology is not likely to be sustainable without addressing the synergy between BIM, integrated project delivery (IPD), and sustainability (Becerik-Gerber and Kensek 2010). Additionally, deploying BIM technology motivates significant changes in widely-adopted business practices in the AEC industry (Succar 2009). Therefore, business owners need to assess and align BIM with their defined strategy (Smith and Tardif 2009). Despite much technological interoperability already being developed, according to Eastman et al. (2008), business interoperability is still limited at this point in time (Taylor and Bernstein 2009). To address the current challenges of the adoption of BIM technology, this study attempts to answer the following questions: (1) What are the key factors for the assessment of BIM performance and how do they impact project and company performance, and (2) How can the BIM-induced improvements in project and company performance be measured?

2. Research Objectives and Scope

The objective of this research is to enable the assessment of the evolution of BIM technology adoption among AEC companies, with the current focus on those in Taiwan. The work presented in this paper is only the first step towards identifying, compiling, and validating key performance indicators (KPIs) for BIM technology adoption. The authors have looked for KPIs from both the barriers and benefits of BIM implementation. To realize the objective, the research is divided into three phases:

- Phase 1: identifying, compiling, and validating the decision-making and technology-implementing factors (DMTIFs) for BIM adoption by conducting questionnaire surveys among BIM experts and practitioners from both the academia and the industry;
- Phase 2: aligning the key decision-making and technology-implementing factors from phase 1 with the company and project performance metrics: efficiency (productivity) and effectiveness through analysis of case studies;
- Phase 3: benchmarking those performance metrics from best practices (learning by doing) against the existing assessment tool(s), for instance, the National BIM Standard (NBIMS) interactive Capability Maturity Model (I-CMM) (McCuen and Suermann 2007), in order to develop a set of professional guidelines.

This paper covers phase 1 of the research study and also discusses the extension of Taylor and Bernstein's work (2009) on paradigm shift of BIM practice at the project level to organizational level, but excluding the industry level. The following sections of this paper cover the aspects of research formulation, research methodology, discussion, and conclusion.

3. Research Formulation

Successful adoption of technologies such as BIM has been investigated by many researchers and has been found to depend on many factors, including the nature and conditions of the organizations, applications, tools, project teams, processes, and business models. It is necessary to assess first the existing technological infrastructure of an organization at the time of an assessment is performed; then the applications for specific purposes can be identified. Tools and project teams are then selected and assigned to realize the applications respectively. The learning and adapting processes in the work environment are also important for adoption of new technologies. Finally, all of the changes in the adoption process usually lead to adjustment of the organization's business models, in turn, the organizational infrastructure. This study is formulated based on known positive and negative impacts of implementing BIM technology.

3.1 Existing BIM frameworks, BIM Protocols, BIM standards and BIM performance measurement tools

Succar (2009) highlighted a tri-axial knowledge framework for BIM: BIM fields, BIM stages, and BIM lenses. Similarly, Jung and Joo (2011) proposed a BIM framework that incorporates BIM technologies, BIM construction business functions, and BIM perspectives. The difference between these two BIM frameworks is that the latter has accounted for construction business processes. These frameworks have provided roadmaps for the effective implementation of BIM technology. However, further efforts are needed on each sector in order for success to be realized. For instance, Succar (2010) identified five components for BIM performance measurement: BIM capability stages, BIM maturity levels, BIM competencies, BIM organizational scales, and BIM granularity levels. However, BIM performance metrics, key to performance assessment, were not introduced.

Khemlani (2006) reported the Contractors' Guide to BIM of the Associated General Contractors of America (AGC). The guide explained four critical factors contractors need to take into account when getting started with BIM: BIM tools, BIM processes, parties' responsibilities, and risks associated; However, some shortcomings have also been found, For instance, model levels of development and model roles and responsibilities are also necessary in the development of BIM execution plans, as required by the AIA Document E202-2008 (2008), SAO State of Ohio BIM Protocol (2010), and CIC Research Program BIM Project Execution Planning Guide (2010).

According to NIBS (2007), the National Building Information Model Standard (NBIMS) defines minimum BIM standards as a baseline for information exchange requirements that can be evaluated using the Capability Maturity Model method. Eleven areas of interest were identified as the main characteristics of BIM practices and processes, and these would be used to measure the maturity of BIM implementation with respect to the organization's capabilities. However, this method lacks the ability to address the common core functions in any company, such as marketing/business development, human resources, finance, information technology, and operations (Smith and Tardif 2009). This is likely to hinder the adoption of BIM technology in any company.

Deriving key elements from existing BIM frameworks, protocols, standards, and performance measurement tools, this research study formulates a comprehensive framework by addressing the shortfalls of existing frameworks and introduces pragmatic solutions. The framework presented in this study comprises the various elements of organization, applications, tools, project teams, process, and business models; aspects that tend to evolve along the BIM stages when BIM is implemented in an organization.

3.2 Assessment framework for BIM technology adoption

A conceptual assessment framework is proposed for BIM technology adoption, as shown in Fig.1. The framework is designed to accommodate the six components of two-layer BIM adoption/performance metrics and four BIM adoption stages in which BIM technology diffuses in an organization. The six components are organizations, applications, tools, project teams, processes, and business models, which are interlinked by two-layer BIM adoption / performance metrics in the center for each BIM adoption stage. The maturity of BIM competence may horizontally shift from the BIM adoption layer to the BIM performance layer at each BIM adoption stage before it enables vertical advancement to the next BIM adoption stage, namely, from visualization to coordination, then to adaptation, and finally to integration. The process of BIM technology adoption is divided into steps and stages. There are six steps for a cycle of each layer at each stage: 1. Organizations, 2. Applications, 3. Tools, 4. Project teams, 5. Processes, 6. Business models.

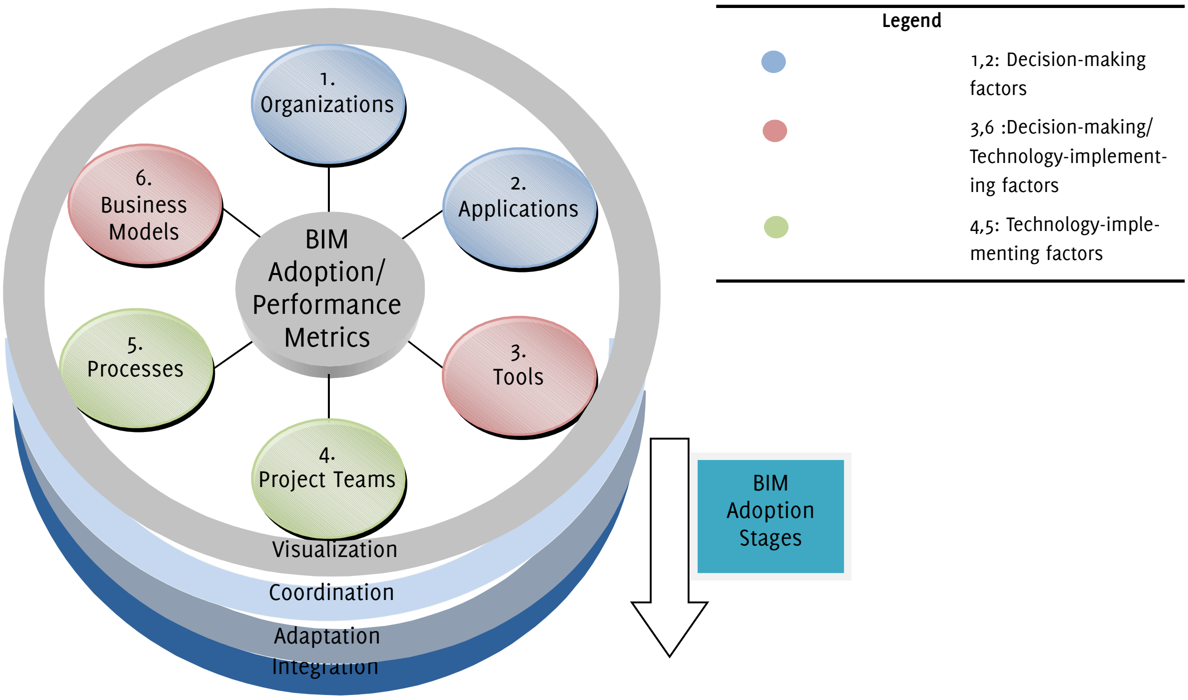

Fig. 1: Conceptual assessment framework for BIM technology adoption

BIM adoption/performance metrics

BIM adoption factors represent the critical success factors (CSFs) that decision-makers use to decide "objection or no objection" for a new technology. At this point three main categories of factors, namely perceived benefits, internal readiness, and external pressure, have been identified by Liu et al. (2010) based on Chwelos et al.'s (2001) work on the adoption of a new technology. BIM performance metrics measure work performance after BIM technology has been deployed. Identifying measurable metrics is necessary for the assessment of BIM performance. Measurable metrics can directly or indirectly represent the performance characteristics, and it is also equally important for those metrics to be specifically tailored for a project and an organization, while still remaining adaptable for application to the entire construction industry. Thus, BIM performance metrics are considered for performance measurement at both project and firm levels.

BIM adoption stages

BIM capability stages are defined by Succar (2010) as "stages representing transformational milestones along the implementation continuum". Adopting BIM appears to gradually evolve in several stages of competencies, depending on many factors which are categorized into six main aspects, namely organizations, applications, tools, project teams, processes, and business models by this research. For example, Succar (2009) proposed a framework with five BIM stages: pre-BIM, object-based modeling, model-based collaboration, network-based integration, and integrated project delivery (IPD). However, the key parameters influencing the adoption of BIM technology had not been clearly addressed in the framework. Complementarily, Taylor and Bernstein (2009) studied the BIM project experiences and the BIM electronic file sharing that change with the four defined BIM paradigms in project networks: visualization, coordination, analysis, and supply chain integration. Adopting some ideas from Taylor and Bernstein's work (2009), this research proposes four BIM adoption stages for both company and project levels. The definition of each stage is provided in the following paragraphs:

Visualization, the first BIM stage, refers to creating images, diagrams, animations, or simulations to communicate aspects such as design intents and options, construction sequences, site logistics, construction methods, and/or site safety.

Coordination, the second BIM stage, refers to the improvement of communication efficiency by sharing electronic model files across disciplines.

Adaptation, the third BIM stage, refers to the adjustment of a new technology, process and work environment to the organization's own sub-organizations and the gradual diffusion of the use of the technology throughout the entire organization.

Integration, the fourth BIM stage, refers to making maximum use of technology deployment by pooling resources and expertise from different sources after internal capitalization and stabilization at the adaptation stage.

Organizations

The 'Organizations' factor represents the decision-making process of an organizational infrastructure due to changes in the characteristics of an organization after a new technology is introduced and diffused in order to adapt to new challenges. The driving forces are believed to be both internal and external. For instance, Olatunji (2011) explored four different organizational structure models that may require adjustments to attune BIM. The shift of organization structure models leads to redesign of new strategies for services and development of new skills. Likewise, Succar (2010) identified organizational scales as one of the five key components of BIM performance measurement. The granularity of the organizational scale is at macro level: markets and industries, at meso level: project teams and at micro level: organizations. Implementing BIM in an organization has been found to lead to disconnect in professional communication and coordination. For example, Dossick and Neff (2010) explained that one of the causes of division within the organization was the tensions between obligations tied to individuals' scope of work, project goals, and company goals. Strong leadership can resolve this division. Besides, Andresen et al. (2000) and Hartmann and Fisher (2009) identified that immediate perceived benefits are closely tied to IT investment and implementation. This has been confirmed by other researchers, namely, Liu et al. (2010) who ranked top management support as the most influential factor on decision-making, followed by perceived benefits. Won and Lee (2010) also identified that BIM software, BIM functions, and BIM pilot projects are critical factors for BIM project success. Furthermore, an organization decides to adopt BIM technology either in-house or by outsourcing, depending on their existing infrastructure (AGC 2006).

Applications

The 'Applications' factor refers to the decision-making for specific BIM objectives that BIM users or an organization desire to accomplish. In other words, aligning business strategies of an organization down to operations may require the definition of clear and appropriate applications in order to harness existing resources and infrastructure. For example, computer-aided design/drafting (CAD) technology has been adopted as a prime tool to assist in the completion of tasks in the AEC industry before the ground-breaking BIM technology has been introduced. To communicate design intents and visualize construction processes requires significant efforts in converting from 2D drawings to 3D or 4D CAD (Koo and Fisher 2000; Bouchlaghem et al. 2005). Furthermore, most practitioners have applied the models for only one application area, implying current ineffectiveness and inefficiencies of using BIM. For example, Hartmann, Gao, and Fisher (2008) evaluated 3D/4D model application in 26 construction projects and found that most of the projects have implemented only one application for one project phase. In addition, according to AGC (2006), the Contractors' Guide to BIM reported that "most contractors are likely to start using BIM through partial uses" for early BIM experiences. The BIM Project Execution Plan Guide by the CIC Research Group (2010) recommended that the measurable goals of a company have to be linked to a project by the specific BIM uses or benefits.

Tools

The 'Tools' factor represents both the decision-making and implementation of software, hardware, and services that an organization needs to tailor the specific uses after assessing the infrastructure of an organization and determining which applications are best suited to both company and project goals. Selecting BIM tools which match with the current competencies and capacities for further skill development of personnel for each area of application may lay the foundation for the successful adoption of BIM technology. For example, AGC (2006) attempted to set the selection criteria for BIM tools after specific BIM objectives had been determined by a company. Shah (2009) asserted that for mitigating operational difficulties and for adopting BIM technology from CAD technology, the current status of technical infrastructure of the organization has to be evaluated carefully against the benefits and challenges of emerging technologies, in order to make the shift from CAD to BIM technology more natural. Khemlani (2008) reported that balancing between older and newer technologies within HOK firm's technical infrastructure would avoid drastic impacts on the firm's productivity.

Project teams

The 'Project teams' factor refers to the implementation through successful teamwork of BIM projects after the applications and tools of BIM have been defined. The construction industry is well-known as a project-based business, and construction project is both unique and temporary. Therefore, forming a project team within a collaborative environment is crucial for each project as it is one of the major driving forces for project success. The assembled team has to work together and effectively and efficiently respond to the project and individual goals. It should be noted that the project goals must be tied to the company strategies (Bernold and AbouRizk 2010; CIC Research Program 2010). For example, Dossick and Neff (2010) outlined that the conflicts between an individual's scope of work with project's goals and company's strategies are inherent in organizations and cultural divisions and project-based leadership may substitute for stronger cohesion in the project team and organization. The AIA California Council (2007) has set forth a project delivery method called Integrated Project Delivery (IPD) which integrates people, systems, business models, and practices into a process that is able to harness the talents and insights of all project participants throughout all phases of design, fabrication, and construction in order to reduce waste and optimize efficiency in a collaborative manner. It is necessary to build an appropriate project team at early stage. However, this project delivery method does not guide how it can be attached to the BIM. For instance, Staub-French and Khanzode (2007) performed case studies on the modeling responsibilities with project team's roles and responsibilities within the scope and the level of details of modeling across project stages. They found that the assembly of a project team with appropriate assignment of the team members' roles and responsibilities for each modeling process and for the level of details of the models are necessary to leverage the 3D/4D technologies. Besides, trust and respect among team members enables barriers to be overcome. Trust is a key that leads project success, especially for large construction projects (Bachelder 2010).

Processes

The 'Processes' factor represents the execution requirements and workflows for implementing BIM applications into projects after the applications and tools of BIM have been defined. At the macro level, the overall execution plan for all the applications need to be defined and arranged according to project phases. The plan may include items such as owner-defined requirements (Ohio DAS, 2010), model work breakdown structure (CIC Research Program 2010), lean process or pull flow (Sacks et al. 2010 and Eastman et al. 2008), step-by-step testing with pilot projects (Arayici et al. 2011), and submittals and approval (AGC 2006). At the micro level, the plan is further decomposed into detailed execution sub-plans for individual applications. The items included in these sub-plans may be, for example, detailed levels of the model, responsible party for the model (AIA 2008; Leite et al. 2011), BIM models built on 2D to 3D conversions or direct 3D models (AGC 2006), and BIM execution plan for each BIM deliverables at each project phase (Ohio DAS 2010).

Business models

The 'Business models' factor represents the decision-making which is based on the outcome being induced by the BIM implementation. In other words, the decisions cannot be made until BIM implementation testing is complete. This is for any business model that is fitted to the collaboration and integration process be considered. For example, the CIC research program (2010) listed delivery methods, procurement methods, and payment methods as key business processes. In addition, Oberlender (2000) recommended that project delivery methods, selection criteria for procurement, terms of payment, and contractual relationships have to be considered for any project.

4. Research Methodology

Our research methodology is comprised of: (a) questionnaire survey, (b) interview, and (c) case study (Fellows and Liu 2008). A comprehensive set of 123 factors were compiled based on a review of literature and the authors' observations after a series of refinements conducted between April 15 and August 30, 2011. These were then grouped into six groups of factors: organizations, applications, tools, project teams, processes, and business models.

4.1 Data collection

The survey is being conducted with business owners, managers, architects, engineers, designers, contractors, sub-contractors, and BIM operators who have had experiences using CAD technology and are now in the process of changing to BIM technology. The 123 factors are organized into 52 'organizations' factors, 26 'applications' factors, 11 'tools' factors, 11 'project teams' factors, 19 'processes' factors, and 4 'business models' factors, as presented in Table 1. All questions are semi-structured and open-ended. The questionnaire has been developed in both Chinese and English language, and will be distributed to the respondents according to target companies and professional organizations. A sample portion of the questionnaire is presented in Fig. 2.

4.2 Data analysis

A 5 point-Likert scale is used to rate the respondents' perception on a total of 123 factors. Respondents are asked to score the importance of factors ranging from (1: unimportant, 2: of little importance, 3: moderately importance, 4: important, 5: very important). Scores above 3 are considered high scores and below 3 as low scores, with 3 as the cut-off or baseline score. Key factors are validated based on the mean score above 3 from all respondents for each factor under each BIM adoption/performance metric (Luu et al.

2008; Lam et al. 2007). Each BIM adoption/performance metric is weighted in relation to another one across all BIM adoption/performance metrics to determine dependency and interdependency between the factors to be measured (Kagioglou et al. 2001). The factors that are added by the respondents for open-ended questions will not be used in the weighting process, but retained for future consideration. The BIM decision-making and technology-implementing index (BIM DMTII) is to be established as the product of the mean score and the weight of BIM adoption/performance metrics (Tucker et al. 1986). The formula is shown below:

$$BIM\ DMTII = w_o O + w_a A + w_t T + w_{pt} PT + w_p P + w_{bm} BM$$

where w_i is the weight and O, A, T, PT, P, and BM represent the mean scores of organization, applications, tools, project teams, process, and business models, respectively.

The BIM DMTII scale, which can be derived from BIM DMTII, is the ratio of BIM DMTII over 5, i.e. from the 5-point Likert scale. The rate is 40% or less for very poor, above 40% to 60% or less for poor, above 60% to 80% or less for moderate, above 80% to 90% or less for good, and above 90% for very good performance.

From the survey results, we expect to obtain key factors for BIM adoption/performance metrics together with the weighting for BIM adoption/performance metrics and the determination of BIM stages. We also expect to collect and analyze a list of additional factors recommended by respondents.

5. Discussion and Conclusion

As our survey is in the process of being conducted, we are not yet able to draw any conclusions. We expect to complete the questionnaire before October 2011 and to present the updated results at the CONVR 2011 conference. In summary, we expect to have the key factors for the six components of BIM adoption/performance metrics, the weighting for the six components, and the BIM decision-making and technology-implementing index (BIM DMTII) or scale. BIM adoption/performance metrics with higher indices will have more influence on the decision-making and technology-implementing for the adoption of BIM technology than the ones with the lower indices.

5. BIM 專案團隊

5.1 您認為組成「BIM 專案團隊」的重要因素為何？

Please identify the importance of the technology implementing factors for project teams?

	因素	重要性				
		非常不重要	不重要	沒意見	重要	非常重要
1	BIM 專案目標(容易理解、預測、速率、效率) Project goals for BIM projects (clear, measurable, effective, efficient)	☐	☐	☐	☐	☐
2	改變專案成員的角色及責任(不同的專案階段及 BIM 交付階段) Change of team members' roles and responsibilities for BIM projects (project phases and BIM deliverables)	☐	☐	☐	☐	☐
3	團隊成員資格審查(資源、能力、經驗) Need for pre-qualification of team members (resources, competency, experience)	☐	☐	☐	☐	☐
4	滿足專案目標及團隊目標(滿意度、期望、提升價值、文化、作風) Match project goals with team goals for BIM projects (satisfaction, expectation, valued-added, culture, style)	☐	☐	☐	☐	☐
5	共享風險及獎勵 Shared risks and rewards that are tied to project success	☐	☐	☐	☐	☐
6	分享資訊及溝通協調(充份、即時、公開) Information sharing/ communication protocol (sufficient, timely, open)	☐	☐	☐	☐	☐
7	以團隊為考量的決策(對專案或團隊提升價值或好處) Team-based decision making for value-added or benefits to project and team	☐	☐	☐	☐	☐
8	交叉訓練(工作輪調) Cross training (job rotation)	☐	☐	☐	☐	☐
9	工作環境 Workspace environment	☐	☐	☐	☐	☐
10	早期參與 Early involvement of project teams	☐	☐	☐	☐	☐
11	專案團隊間的信任及尊重(中立) Trust and respect among project teams (neutrality)	☐	☐	☐	☐	☐
12	其他（請描述）：	☐	☐	☐	☐	☐

Fig. 2: Sample portion of questionnaire

Table 1: Factors influencing BIM technology adoption

Factor Groups	Factors
Organizations (O)	52 factors: Perceived benefits from BIM, cost leadership in market, differentiation in market, focus/niche in market, competitive advantage, efforts of adaption to new project characteristics, efforts of adaption to new organization characteristics, need for organizational restructure, support from top management, corporate/project leadership style, corporate management style, disposal subsystem, procurement subsystem, operations/production subsystem, human resource/maintenance subsystem, adaptive subsystem, managerial subsystem, quality assurance subsystem, strength of culture, worker attitude and ethical behavior, individual and group motivation, level of bureaucracy, cross-cultural differences among members of organization, managing resistance to BIM change, need for process reengineering, modification of existing CAD-based systems and processes, building the model using in-house resources, building the model using outsourcing, investment cost, BIM project experiences, need for BIM personnel and training, financial resources, technical competence, technological capability, human capability/resources, innovation capability, resource and development capability, organiza-

	tional learning capability, effectiveness of information flows/communication flows, level of joint venture, partnership at corporate and project levels, strength of relationships with other parties, ratio of internationalization, construction supply chain management, politics and law conditions, socio-economic conditions, government policies, BIM standards, codes, rules and regulations, industry/market trend, pressure from competitors, client's request for BIM, flexibility/adaptability.
Applications (A)	26 factors: photorealistic rendering and animation, site layout planning and site safety (site logistics), 3D modeling, design validation/virtual design review, 4D construction sequencing and simulation, quantity take-off and cost estimating, 5D cost control and simulation, structural analysis and design, MEP analysis and simulation (HVAC), energy analysis and simulation, acoustical analysis and simulation, environmental analysis and simulation (airflow/CFD), thermal analysis and simulation, model checking and validation, design coordination, analyzing design options, BIM models for shop drawing, BIM models for fabrication, bid package preparation, extract quantity information from BIM models for procurement, construction coordination and tracking, construction project coordination (real-time site coordination), facility management, remodeling and renovation, BIM models for information sharing and knowledge management, and disaster management.
Tools (T)	11 factors: simplicity (easy to learn and use), functionality (completeness, specific needs), interoperability (data exchange formats), long-term providers (vendors/suppliers), technical support including training, collaborative environment (network), efficiency, reliability (robustness), hardware requirements, initial investment cost, and maintenance and upgrade cost.
Project Teams (PT)	11 factors: project goals, change of team members' roles and responsibilities, pre-qualification of team members, matching project goals with team goals, shared risk and reward tied to project success, information sharing and communication protocol, team-based decision making, cross training, workspace environment, early involvement of project team, and trust and respect among team members (neutrality).
Processes (P)	19 factors: owner-defined BIM requirement during design and construction, owner-defined requirement for post construction, different applications according to project phases throughout project lifecycle, appropriate tools to perform the applications, 3D modeling converts 2D to 3D models, 3D modeling, model work breakdown structure according to construction classification systems, lean process/pull flow, model content requirements and reference information for each level of development (level 100, level 200), responsible parties for each process at each project phase, breakdown a specific application into a set of processes, map processes within a specific application, model content requirements and reference information for each level of development (level 300, level 400, level 500), responsible parties for a set of processes at each specific application, logical checks for decision at important points for a set of processes at each specific application, BIM deliverables at each phase of the project's lifecycle, BIM models for submittals and approval, step-by-step testing with pilot projects to perceive immediate benefits and improve workflow process from operational level to organizational level, BIM execution plan contains the organizations, applications, tools, project teams, processes, and business models.
Business Models (BM)	4 factors: contracting/contract arrangement, project delivery methods, selection criteria for procurement, and terms of payment.

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SIMULATION OF MAINTENANCE OPERATIONS IN THE LIME PRODUCTION

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1. Uncertainty in the Planning of Maintenance Operations

A large uncertainty for the maintenance planner, e.g. in a production company in the building materials industry, exists whether the planned processes of the maintenance operations will really achieve a set given goals – such as the on-time completion (due date reliability) of the maintenance operations or implementation of cost optimal usage of resources – is suitable, as well as, if the objectives are even achievable, due to when disturbances that can consistently occur during maintenance operations. In this context, 95 % of the companies participating in a scientific study about future strategies of the German construction and plant engineering industry stated that they would expect an efficiency increase through continuous controlling of all risks (see Seefeldt, Pekrul 2005, p. 19).

With their predominantly traditional methods and organizational procedures, the building materials industry is facing large planning uncertainties. Considering e.g. maintenance operations and disturbances which can occur during operation, it is often asked, whether planning tools and procedures from other industries can be adopted by them. Consequently, the experience gained in the manufacturing industry and the related planning instruments come into focus. One approach which has often proved its value in manufacturing companies is the simulation of production processes. Using this technique, e.g. predictions regarding the expected production situation as well as the effectiveness of resource utilisation can be made (Zülch, Börkircher 2006, p. 277).

2. Opportunity for Process Simulation

A suitable approach can be thus seen in the development of a novel, simulation-based method to support the planning of maintenance operations in a building materials industry and to analyze the performance of its maintenance operations (see figure 1 for the structure of the simulation procedure).

The maintenance planner can be handed a tool with which he can already identify maintenance process risks within the planning stage and which shows him the consequences resulting from disturbances. From the simulation results the maintenance planner can draw conclusions for his maintenance operations in order to hold corrective measures or alternative planning solutions as well as process alternatives.

The process simulation provides the maintenance planner thus a risk assessment of the maintenance operations regarding simulated used capacity costs and cycle time on the basis of planning and process changes, and also in respect of resource utilisation and due date reliability of maintenance operations. Disturbances can be seen as a system workload which can affect the logistic and monetary goals of a company. This can lead to new insights into the winding-up of maintenance operations that would otherwise be possible only during the real execution.

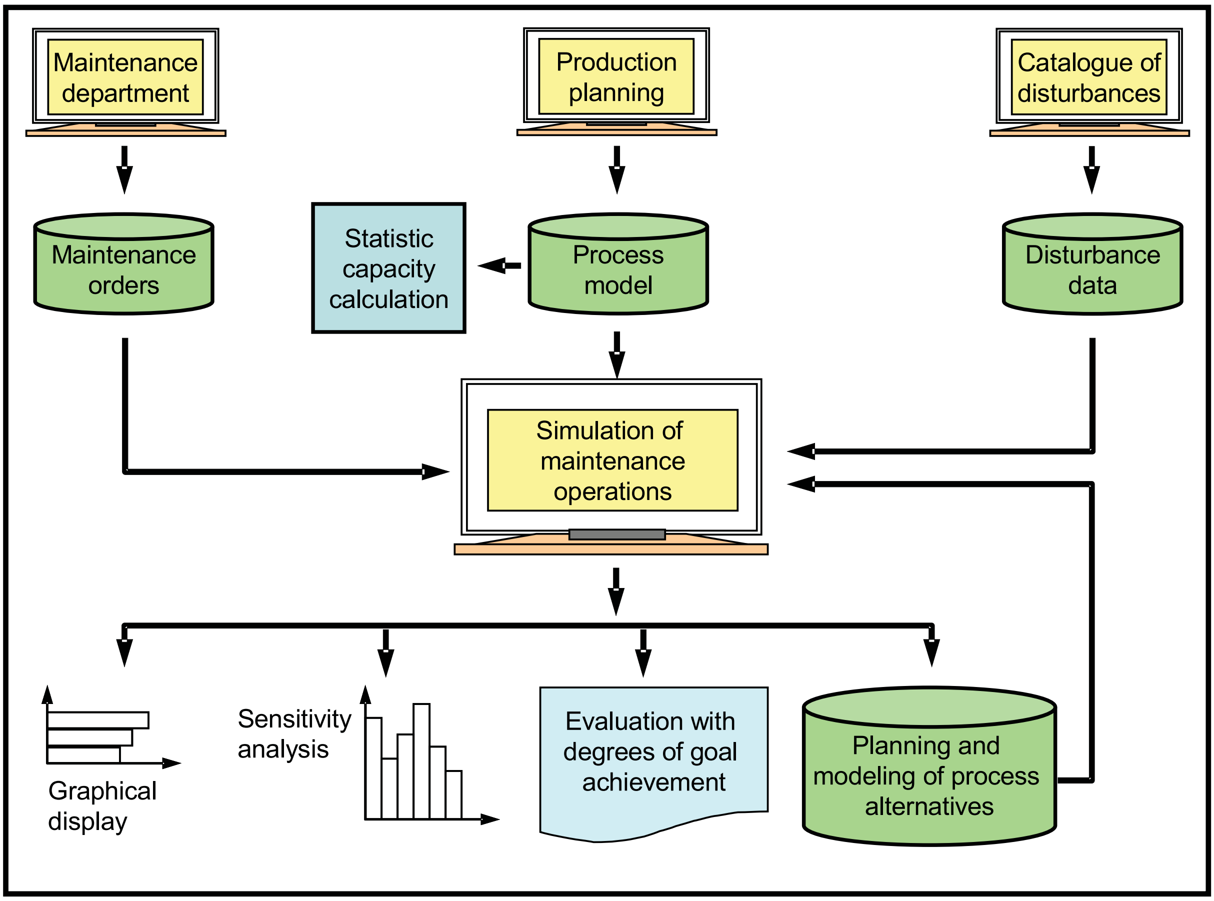

Fig. 1: Structure of the simulation procedure (following Zülch 1992, p. 42)

3. Modeling of Process Alternatives

By the planning of corrective measures and its simulation it can be verified to which extent an initially planned execution of maintenance can be made more robust when taking process uncertainties into account. The robustness of a maintenance process can be e.g. investigated by targeted improvement of the initial planning solution in an iterative process. Here, the change of operation sequences or parameters such as allocation of personnel can be inserted into the simulation model. This approach is practically quite appropriate because it reflects on the one hand the common everyday task of a maintenance planner to develop alternatives. On the other hand, the experienced maintenance planner is able to restrict alternatives to be examined within a given process section. This is always advisable when the maintenance operations are very extensive and complex. In such a case, the maintenance processes can be separated into smaller self-contained process stages, e.g. maintenance operations concerning a single plant section or more detailed regarding single system components. The development of process alternatives must be seen as a target-oriented, methodically and systematically problem solving process.

4. Used Simulation Tool

For this purpose, the discrete, event-driven simulation tool *OSim* (Objekt-*Sim*ulator; see for details Jonsson 2000, pp. 181; Zülch, Fischer and Jonsson 2000) was used as a basis. *OSim* was developed at the *ifab*-Institute of Human and Industrial Engineering of the Karlsruhe Institute of Technology (formerly University of Karlsruhe). With this simulation tool a broad field of networked processes and even programmes of them can be modelled and evaluated, both in goods producing and services industries. For its application in the construction and related building materials industry, a specialized version was designed and implemented into the new software tool *OSim-BAU* (Objekt*sim*ulator für die *Bau*produktion).

In the following, the simulation-based method will be applied to a pilot study. This case example concerns a maintenance planning as well as reparation processes of a rotary kiln in the lime industry. The simulation analysis will show that the originally for construction operations developed simulation approach can also be implemented for disturbance containing processes in the construction-related industry. In the simulation tool, processes for the construction industry as well as for the building materials industry are modelled as netgraphs; netgraphs can be regarded as process plans.

4.1 Pilot Study in the Lime Industry

For the production of quick lime two types of kilns are used in the lime industry: the normal shaft kiln as well as the rotary kiln. A rotary kiln, which is regarded here, is made up of a so-called lepol grate on which lime stone coming from the quarry is put for the pre-calcination, the rotating duct with its refractory lining, the burner unit, the rekupol cooler, exhaust gas lines, dedusting facilities, cyclones, electrostatic precipitators, and the exhaust gas fan with the succeeding chimney (see figure 2).

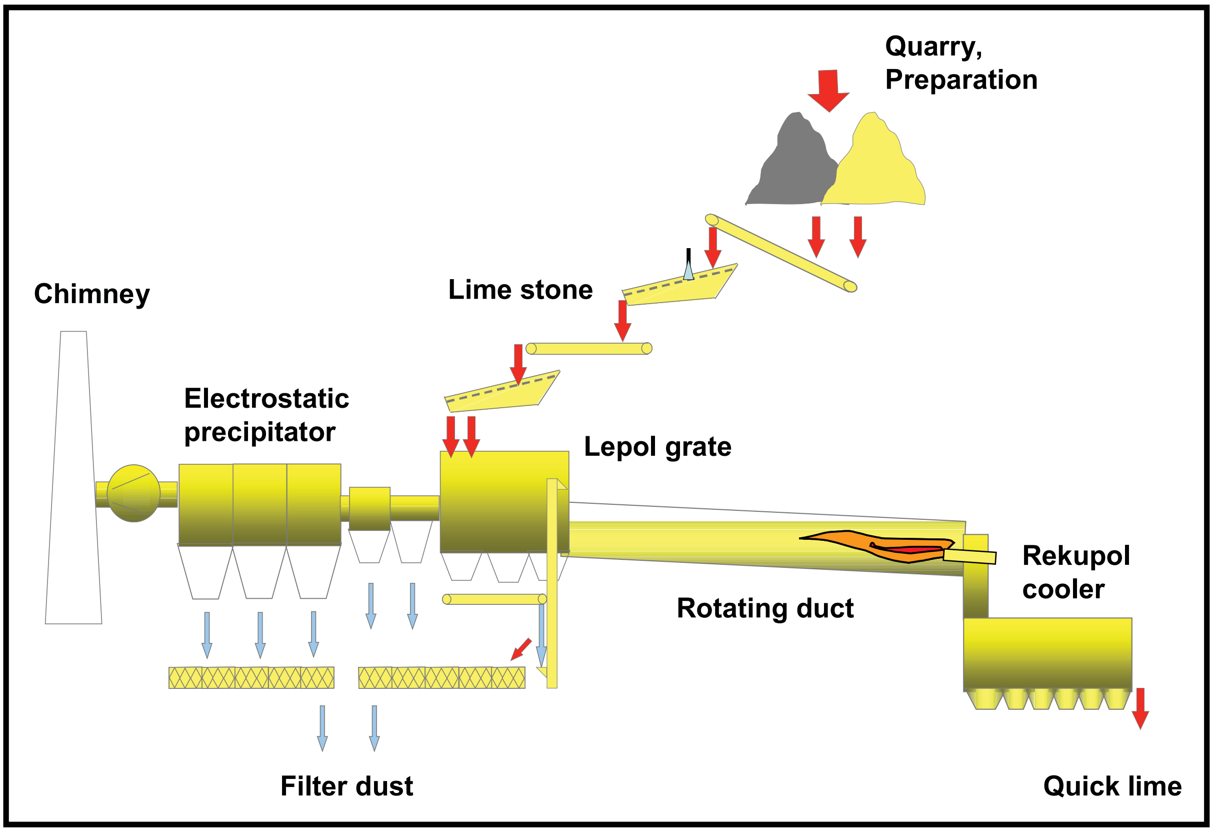

Fig. 2: Principal sketch of a rotary kiln

The lepol grate which is positioned upstream to the rotating duct is the production-related core of the entire burning system. By thermal decomposition in the lepol grate, lime stone is formed into quick lime by extruding CO_2. The temperatures used are usually depending upon the product quality; the range is about 1100 to 1350 °C.

The lime industry is facing increasing energy costs. Therefore it is particularly important to aim at a continuous rotary kiln operation. By a high amount of produced quick lime, the specific, to a ton of quick lime related energy costs, can be reduced. A continuous and trouble-free operation of a rotary kiln is ensured by maintenance at regular intervals. Special attention must be paid to the critical system components like lepol grate, burner unit, and refractory lining of the rotating duct, as they are the highest cost factors and, second, the bottlenecks in the schedule of maintenance operations. The planning of the maintenance measures has also a significant impact on the completion of the maintenance operations in due time.

4.2 Process Alternatives

The down times of a rotary kiln are usually set to 18 days in which the above mentioned critical system components have to be revised. In the regarded case, the duration of the entire work exceeded a span from 2.5 to almost 5.5 days in the past. This was due to various disturbances and interruptions during the maintenance operations which caused production losses in the upper five-digit Euro range. Reasons for this was that the maintenance planning was not configured for each individual craft, difficulties during the replacement of lepol grate plates as well as the lepol grate chain due to uncoordinated and self-hindering operations, a delay in the removal as well as the re-implementation of a new refractory lining and diverse friction losses during the implementation of the new burner unit.

To improve the maintenance operations, various process alternatives have been developed by the production department of the company in cooperation with the maintenance department. Hereby, it was focused on the following stages of work: maintenance planning, exchanging of refractory lining, checking the burner control system and replacing of lepol grate plates.

A total of 144 different process alternatives have been developed in order to analyse the maintenance operations at the rotary kiln. The full-factorial experimental plan in figure 3 shows how the 144 alternatives from the individual netgraphs are set up. The main difference between the individual alternative netgraph compared to the netgraphs of the initial process exists in the simultaneous winding-up of the individual maintenance operations for a rotary kiln. This leads to a higher degree of parallelism for the total process netgraph of the maintenance operations. Furthermore, the series of operations were changed for several alternative process netgraphs in order to check if technical changes within the processes can lead to a better degree of goal achievement (for definition see e.g. Zülch, Grobel and Jonsson 1995, pp. 316). The improvement methods are here not explicitly documented for reasons of confidentiality.

Process alternatives of maintenance processes at a rotary kiln	Alternative process plans			
	Maintenance planning	Refractory	Burner control	Lepol grate
1	0	0	0	0
	1	1	1	1
…	2			2
144	3	2	2	3

Caption: 0 = Initial situation; 1,2,3 = Alternatives

Fig. 3: Full-factorial experimental plan for the testing of process alternatives in the maintenance

4.3 Generation of Disturbance Scenarios

In this pilot study, the maintenance planner does not consider any particular disturbances that he has observed in the past, but instead leaves the maintenance operations open to all possible disturbances that may occur. The focus of the case study lies on the automatic generation of disturbance scenarios. Single disturbances are hereby randomly created under the use of the typical model parameters, namely intermediate arrival times and disturbance removal times. Respective statistical distributions of these parameters are then aggregated into a disturbance scenario for a series of simulation runs.

A disturbance scenario is generated for every simulation run and consists of a certain amount of the following three disturbance categories: process disturbances, personnel disturbances and material disturbances. The model generator creates each disturbance as a "virtual" activity with a stochastic duration. The effect of the generated disturbances, for example for process-related disturbances is defined as follows: A disturbance blocks or the virtual activity disturbs a certain operation of the process netgraph; thus it is integrated into the existing operation as a virtual "time buffer". The further processing of the operation can only recommence, after the disturbance time has run out.

Disturbances that have occurred during the realized maintenance operations in the past could not be reproduced, nor could the absenteeism of the personnel. Instead, a pragmatic approach was used by setting the share of disturbances for process-related reasons (figure 5, index c) to approximately 65 %, for personnel-related disturbances (index c) to approximately 10 % and for material-related disturbances (index h) to approximately 25 %. Furthermore it was assumed that a maximum of 50 disturbances can occur during the maintenance operations. According to a defined algorithm for generating stochastic disturbances, 64 different disturbance scenarios were investigated for each tested process alternative. The number of scenarios here considered, was esteemed as enough in order to quantify their effects on the goal achievement of the process alternatives. Under these assumptions the maximal variation for process-related disturbances is 8 %, for personnel-related disturbances 4 % and for material-related disturbances 2 %. With regard to the total process plan of an alternative, with for example 63 operations that model-wise describe the considered total process plan up to 100 %, means that the set variation of process-related disturbances that (can) appear up to 8 %, result in a rounded quantity of five disturbed operations.

A further assumption was made in accordance with the maintenance department of the lime company, which assumed that all disturbances from the three disturbance categories can occur between six and nine days. The results of a chi-square test for observed disturbances in the construction industry showed that a beta-distribution tended to be assumed for the intermediate arrival times as well as for the disturbance times. The beta-distribution was thus also used for the simulation experiment in this case study. The expected value and the variance of the beta-distribution are calculated with the help of the PERT-parameter for an estimated process time (see Neumann and Morlock 1993, pp. 722). It should though be known that, in general, there are numerous possible distributions that can similarly be adjusted and used as stochastic models for the given empirical distributions.

4.4 Experimental Possibilities and Exemplary Simulation Results

The created simulation method gives the maintenance planner numerous possibilities for testing process alternatives. For example he can analyze the dependence between a planned process alternative and the effects of different disturbance scenarios on it or he can analyze the disturbance robustness of process alternatives that are technologically equal underlying the same disturbance scenarios. The following degrees of goal achievement are considered within the pilot study (see also figure 4): lead time degree (GLD), capacity costs (GCC), capacity utilization (GCU) and due date reliability (GDR).

Production logistic and monetary degrees of goal achievement	GLD	GCC	GCU	GDR
Highest degree of goal achievement (%) across all alternatives	91	93	81	92
Amount of highest degrees of goal achievement across all alternatives	7	1	14	7
Thereof amount of robust alternatives	3	1	4	2

Fig. 4: Highest attained degrees of goal achievement

For the robustness analysis it is important to check how the output variables of a simulation model react to the scattering of the input variables (disturbance parameters). Variation coefficients for input and output variables can additionally be created and compared to one another; this can end into two cases. First case: The variation coefficient for input variables is larger than or equal to the variation coefficient of output variables. The analysed alternative reduces the scattering of the system parameters and reacts robust. Second case: The variation coefficient for input variables is smaller than the variation coefficient of output variables. The analysed alternative amplifies the scattering of the system parameters and is sensitive to a system workload. As a rule, regarding this alternative, an undesirable intensification of scattering is existent; the alternative reacts non-robust.

From the 144 simulated alternatives in this case study, one can derive that the highest degree of goal achievement corresponded to those alternatives, which proved not to be robust in the analysis (see figure 4). This result demonstrates that high degrees of goal achievement of some alternatives are not necessarily accompanied by a disturbance robustness of these alternatives. It could, however, be determined that the original process plan, which the maintenance department favored, can better be replaced by other process alternatives.

The simulation results in figure 4 are based on the fact that they are calculated as the average degree of goal achievement for all disturbance scenarios. The following example, however, shows that the fluctuation margin of the individual degrees of goal achievement is larger for non-robust alternatives compared to robust ones. In reverse, this means that the disturbances do not affect robust alternatives as much as they do non-robust alternatives. The so-called "influence degree" was introduced at this point in order to prove this theory (also see Heel 1999, pp. 147). The influence of an evaluation criterion comes from the difference of the average of an evaluation criterion, that is reached during a (minimal and maximal) system workload through distribution scenarios as well as a basic alternative, and the minimal determined average degree of goal achievement of all considered alternatives for a (minimal and maximal) system workload caused by disturbance scenarios.

Degree of goal achievement	Disturbance scenario with low system workload for *c*, *e* and *h*: 1 %, 1 % and 1 %									
	Non-robust alternative (No.)					Robust alternative (No.)				
	23	51	52	57	131	22	46	47	70	130
GLD	▼	▲	▲	▼	▼	▼	▲	□	▼	▼
GCC	□	□	▼	□	□	▼	▲	□	□	▼
GCU	□	□	▼	□	□	□	□	▼	□	□
GDR	▼	▲	□	▼	▲	▲	▲	□	▼	▼
Degree of goal achievement	Disturbance scenario with high system workload for *c*, *e* and *h*: 8 %, 4 % and 2 %									
	Non-robust alternative (No.)					Robust alternative (No.)				
	23	51	52	57	131	22	46	47	70	130
GLD	▼	□	□	▼	▼	▼	▲	▲	□	▼
GCC	▼	▲	▲	▼	▼	▼	▲	▲	▲	□
GCU	▼	▼	▼	▲	□	□	▲	□	▼	▲
GDR	▼	▲	□	□	▲	□	▲	▲	□	▼

Caption:			
	Influence degree positive:	0 %-points < Influence degree ≤ 5 %-points	▲
	Influence degree inconsiderable:	-1 %-points ≤ Influence degree < 1 %-points	□
	Influence degree negative:	-6 %-points ≤ Influence degree < 0 %-points	▼
	Index c:	process-related disturbance	
	Index e:	personnel-related disturbance	
	Index h:	material-related disturbance	

Fig. 5: Influence matrix for the degrees of goal achievement of selected robust and non-robust alternatives, for low as well as high system workloads

The disturbance scenario with the smallest and highest percentage of variation, being 1 % as well as the already stated 8 %, 4 % and 2 % for the three disturbance categories, is applied for the following evaluation of the simulation results. Figure 5 depicts a so-called "influence matrix" that entails ten selected alternatives from the simulation runs, consisting of five robust alternatives and five alternatives, which, according to the comparison of the variation coefficients of the input variables with the output variables, are non-robust.

The evaluation of the non-robust alternatives shows that numerous degrees of goal achievements have a negative influence in the case of a high system workload, in contrast to a low system workload. The degrees of goal achievement are maximally 6 %-points lower in comparison to an inconsiderable influence or even up to 11 %-points lower on the basis of a positive influence.

In contrast, one notices an immediate influence in the degrees of goal achievement for robust alternatives, when going from a low system workload to a higher one: The degrees of goal achievement of robust alternatives barely change and reach higher values respectively. The influence of the degrees of goal achievement stays inconsiderable and often reaches a positive value. The reason can be seen in the consideration of the degrees of goal achievement, which are aimed for at a middle system workload. However, if one considers individual disturbance scenarios, one can determine that the influence of the degrees of goal achievement – either negative or positive – compared to that of the two extreme system workloads does not have as rigorous effects on the robust alternative, as it does on the non-robust alternative.

From the results in figure 5 one can assume that the inconsiderable and positive influence can be an indication for the disturbance robustness of an alternative, when a disturbance scenario with low characteristic values is compared to a disturbance scenario with high disturbance parameter values. It can thus be excluded that the degrees of goal achievement of the robust alternatives must be the highest. Crucial for the advantage of an alternative is that the scattering of the degree of goal achievement is contained in a certain goal achievement corridor for different production situations. Disturbance robustness thus tends to mean, keeping the smallest scatterings of the defined alternative inside of the values of the degrees of goal achievement, for all possible system workloads. This can be an indication for the disturbance robustness, which, however still needs to be validated through further research.

5. Conclusion and Further Leading Aspects

The proposed simulation tool assists maintenance planners to already analyze impacts on future maintenance operations systematically in the early phase of production planning. This is not an iterative improvement process – as it can be found in many simulation studies – trying to successively generate as good as possible maintenance operations using certain algorithms. In the used simulation tool, process alternatives are designed manually to respond to any possible disturbances as directly as possible, and this must already be done in an early phase of production planning.

The example of a kiln maintenance process in the lime industry showed that with the aid of the proposed simulation tool it is not only possible to analyze the effects that occur through process disturbances, but furthermore that the so-called influence degrees (see above) can depict how the degrees of goal achievement of alternatives can change due to different disturbance scenarios. Due to the limited size of the described case, further simulation studies must be performed in order to validate the obtained findings.

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A CAMERA BASED UBIQUITOUS PAVEMENT CONDITION ASSESSMENT FRAMEWORK

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ABSTRACT: *Current practice of pavement condition assessment is still a predominantly manual task and a certain amount of subjectivity and experience of the raters have an undoubted influence on the final assessment. Due to high costs, the assessment cycle for critical roadways is one year and for smaller, local roads much longer. Therefore, this paper presents a solution for pavement assessment under which the rear-view (backup) camera of vehicles can be replaced with a high-speed, high-definition camera that can tilt downwards during driving forward at daylight hours and is equipped with a strong LED light to compensate for occasional shadows. The video feed from the camera is processed to detect frames with potential surface distresses and elevation distresses. For frames with possible distresses, in-car GPS information is added for location information. Frames with potential elevation distress data are then used to generate a dense 3D point cloud for an in-depth analysis and classification of distresses based on state-of-the-art detection tools. The distress data (type, location, geometry, and appearance) are further processed to assess severity by comparing the measured attributes with those suggested in established assessment codes. Finally, findings from the network of cameras (the location and magnitude of distresses) are transmitted to Google Maps. Preliminary results of pothole detection in pavement images and videos - as part of the overall framework - have achieved about 85% recall. This suggests the applicability of such a system for road network pavement assessment. The framework can possibly provide frequent, reliable and accurate detection and localization of distresses in order to assist DOTs in pavement condition assessment.*

KEYWORDS: *vehicle back-up camera, pavement evaluation, distress assessment, image-based analysis*

1. Introduction

The roadway network of a developed country contains thousands of centerline kilometers of pavement. This network consists of bituminous, concrete, or composite pavements ranging in condition, age, and performance. Monitoring and assessing the condition of these pavements are still primarily manual and time-consuming tasks. Moreover, a certain amount of subjectivity and the experience of the raters also have an undoubted influence on the final assessment (Bianchini et al. 2010). Also, only a 10% sample (first 500 feet of each mile) of the pavement miles is actually inspected and used to perform the assessment rating (MnDOT 2009). The time associated with sensing the whole highway network of a state does not allow for repeated measurements to improve the accuracy and reliability of a survey.

Traditional methods are quickly being replaced by dedicated vehicles that automatically collect pavement data. However, due to high costs, the number of inspection vehicles is very limited (Fugro Roadware 2010; MnDOT 2009), which results in a survey cycle of one year for critical roadways and many years or complete negligence for all other local and regional roads. During that time, existing distresses can degrade public driving comfort, increase gas consumption, and damage vehicles (fatigue failure). Moreover, current Department of Transportation (DOT) surveys do not consider on-road traffic so they cannot capture what distresses have the most significant impact on the driving public and prioritize their repair.

Therefore, this paper presents a framework under which the rear-view (backup) camera of vehicles is replaced with an inexpensive, high-speed, high-definition, camera that can tilt downwards during driving forward at daylight hours and is equipped with a strong LED light to compensate for occasional shadows. In the proposed research, the video obtained from the camera is processed to detect both, surface distresses by using detection methods for distresses and elevation distresses through 3D reconstruction. Initially potential frames with distresses are detected. The in-car GPS information is used to add location information every time a set of frames with potential distresses is detected. Then, using the frames with potential distresses, a dense 3D point cloud is generated for further analysis for detection, classification, and measurement of geometrical properties. These geometrical properties are compared with code standards to obtain the severity of the distress. This information can then be transmitted to Google Maps using the in-car computer. The severity and frequency of reporting a certain distress can then be used to assess its impact on the driving public as well as to feed in-car warning systems assisting upstream drivers in avoiding or minimizing the impact of severe distresses such as deep potholes.

2. Background

The state of knowledge presented here outlines current practices for pavement assessment, the research efforts, and the sensor fusion efforts in automating pavement distress detection and assessment.

2.1 Current Practices in Pavement Condition Assessment

Monitoring the road network of a state with a dedicated inspection vehicle is currently the most effective approach and is quickly replacing traditional methods. For example, the Minnesota Pavement Management Unit collects pavement condition data, calculates surface distress quantities on approximately 60% of the highway system, and provides a Pavement Condition Summary Report (MnDOT 2009) every year. The pavement roughness and surface distress data (cracks, rutting, patching and joint deterioration, etc.) are collected using a sophisticated digital inspection vehicle equipped with digital cameras and lasers. The downward looking cameras capture surface distresses whereas the lasers measure the longitudinal and transverse pavement profile, from which pavement roughness, rutting, and faulting are determined. The collected data is then analyzed manually. FDOT's Florida Automated Faulting Method automatically uses an inertial profiler to detect joints and estimate faulting in concrete pavements (Nazef and Mraz 2010). However, this method can accurately detect only transverse joints and can estimate faulting on jointed concrete.

Another popular type of pavement inspection vehicle, is the Automatic Road Analyzer (ARAN) platform by Fugro Roadware Inc. (Fugro Roadware 2010), claims that it can automatically or semi automatically measure all significant road condition data including longitudinal profile (roughness), transverse profile (rutting), and pavement distress (cracking, potholes). It uses video cameras for surface imaging, optical sensors for distance measurements, lasers for profiling, additional ultrasonic sensors for rutting detection, and accelerometers for roughness measurements. It is well suited for automatic collection of all kinds of pavement distresses and positioning data but, except for the positioning subsystem, each set of sensor data is analyzed separately and independently (Fig. 1, left).

Fig. 1: Pavement inspection vehicle ARAN (Fugro Roadware 2010) and manual assessment work station (MnDOT 2009).

The data collection process is automated by the use of such sophisticated vehicles but the collected data are manually viewed and analyzed. Technicians visually detect and assess distresses based on their own experience and a distress manual (FHWA 2003, MnDOT 2003) (Fig. 1, right). Existing software somewhat assists in the calculation of the quantity of distress, e.g. for describing crack type, severity, extent and location (Fugro Roadware 2010) and hence the calculation of the Surface Distress Index. Manual analysis induces subjectivity and the experience of inspectors has an undoubted influence of the pavement ratings. Moreover, differences in the distress rating can occur due to a difference in the appearance of the pavement surface depending on the direction and angle of the sunlight, pavement temperature and moisture, and the direction from which the raters view the pavement surface (Bianchini et al. 2010).

2.2 Research Efforts in Automating Pavement Distress Detection and Assessment

Significant research has been performed to automate pavement distress detection, assessment, and repair. The most popular proposed methods are based on computer vision algorithms that operate on 2D images to recognize, classify, and measure pavement surface distresses. Several efforts with specific regard to crack detection and assessment, in particular real-time crack analysis (Wang and Gong 2005, Huang and Xu 2006, and Sy et al. 2008), crack classification (Sun et al. 2009, Zhou et al. 2005, and Ying and Salari 2010), crack depth estimation using computer vision (Amarasiri et al. 2010), and even automated crack sealing (Haas 1996, Kim et al. 2009) have been made. Tsai et al. (2010) have critically assessed available distress segmentation methods for crack detection and classification to conclude that these methods have varying performance with varying lighting conditions, shadows, and crack positions and that there is no comprehensive, robust and real-time segmentation method available.

Besides cracks, Zhou et al. (2006) have proposed a wavelet transform based method to support real-time pavement distress detection, isolation, and evaluation based on images of the pavement. Of these, distress detection and screening is currently possible. The method considers only the appearance of distresses; therefore it is unable to address 3D distresses such as rutting. Nguyen et al. (2009) presented an approach to detect joint and bridged distresses using a measure of Conditional Texture Anisotropy (CTA). This approach uses post processing of images obtained from two line scan cameras mounted on a special data acquisition system to detect distresses. Furthermore, adaptive imaging techniques have been successfully applied to detect only cracks and patches, and measure their areas using a digital camera mounted on a mobile laboratory and post processing the images (Cafiso et al. 2006 and Battiato et al. 2007).

Methods for 3D reconstruction of the pavement surface have also been proposed to address the limitations of 2D vision-based methods to detect rutting, bumps, and sags. These 3D reconstruction methods are either based on range sensors or stereo vision. Li et al. (2010) presented a real-time laser scanning system for pavement rutting and pothole detection using an infrared laser line projector and a Gigabit Ethernet (GigE) digital camera for data collection. The laser line transversely covers the pavement lane and the camera captures consecutive laser line image while the vehicle is moving forward. The camera is calibrated and the laser has a frame rate of up to 200 fps. Using this system, 3D profile of the pavement can be obtained in real-time and distresses such as rutting and shoving can be measured. However, this system is insensitive to lighting conditions and pavement texture. The resulting data produced from this system is digital images and laser scanning point clouds. Integration of these two data types is possibly a challenging task.

The Laser Crack Measurement System (LCMS) developed by Pavemetrics Systems Inc. (Pavemetrics 2011a) uses high-speed cameras and laser line profilers to obtain 2D images and high-resolution 3D profile of the road surface. Data can be collected at speeds up to 100km/h under varying lighting conditions for various pavement types. The data is then used to automatically detect and analyze cracks, lane markings, ruts, macro-texture, patches, and potholes. Moreover, the distress analysis results can be used with Pavement Management System to prioritize rehabilitation of the pavement. Similar systems such as Laser Road Imaging System (LRIS) (Pavemetrics 2011b) and Laser Rut Measurement System (LRMS) by Pavemetrics Systems Inc. (Pavemetrics 2011c) help with pavement inspection.

Correspondingly, Wang (2004) and Hou et al. (2007) proposed stereovision based surface models for comprehensive pavement conditioning. With the availability of a 3D pavement surface model, Chang et al. (2005) have shown how to automate pothole identification using 3D laser scanning technology, and Jiaqiu et al. (2009) have developed a method for identifying, locating, classifying, and measuring sag deformations.

However, all the methods presented above use a dedicated vehicle for collecting data. The methods that use laser scanning are mainly limited to elevation distresses, cannot be used to recognize surface cracks, and present limitations such as high initial cost requirement, need for significant power and frequent maintenance. In addition to these, laser scanning can only reconstruct Cartesian point cloud models, while in addition to reconstructing point cloud models, image based reconstruction techniques enable extraction of semantics (e.g. 2D distress detect types, geometrical attributes) through registered imagery (Golparvar-Fard et al. 2009a&b). Laser scanners also suffer from mixed-pixel phenomena (Kiziltas et al. 2008), which requires noise to be manually removed from the data in a post processed stage. Finally existing vision based systems require two or more cameras to be installed on inspection vehicles, which compared to an existing infrastructure of backup cameras makes their application unattractive.

Besides vision and laser scanning based methods, a vibration-based system for the preliminary pavement condition survey has been proposed (Yu and Yu 2006). In analogy to cameras “seeing” a pavement surface, a vibration-based sensor (e.g. accelerometer) “feels” the ground conditions based on the vehicle’s mechanical responses. Yu and Yu (2006) have identified the advantages of a vibration-based system as requiring small storage, being cost-effective and amenable for real-time processing. However, this system does not provide any details about the distress characteristics. Also, the response of a vehicle is modulated with the response of the surveying vehicle so the results cannot be compared unless the service condition of the vehicles is calibrated.

2.3 Sensor Fusion Approaches to Pavement Monitoring and Warning Systems

Although each sensor has its advantages and disadvantages, available single sensor approaches to infrastructure monitoring do not provide sufficiently accurate information to localize and determine the extent of distress (Attoh-Okine and Mensah 2009). As a result, the method of sensor fusion, as a process of associating, correlating, estimating, and combining information gathered from a multi-sensor network, has emerged (Farrar et al. 2006).

Another purpose of sensor fusion for pavement monitoring is to enable the synchronization of damage detection and positioning. The projects BusNet (De Zoysa et al. 2007) and Pothole Patrol (Eriksson et al. 2008b) share the same basic idea of combining vibration sensors with GPS and using mobile nodes to sense road conditions in terms of pothole detection. While in the BusNet project a public transportation based network is proposed, the Pothole Patrol approach generally aims at any kind of vehicle network, but was tested using taxis. Concerning data transmission, in the BusNet project a separate wireless network, consisting of Sensor Units (buses), Sub Stations, and a Main Station, has been set up in order to provide wireless data delivery and data collection service. On the contrary, the Pothole Patrol system uses both Wi-Fi connections and cellular data service to transmit collected data to central servers. In Hull et al. (2006) a distributed mobile sensor-computing platform, called CarTel, is presented. Not focusing on a specific application, it is designed to collect, process, deliver, and visualize data from multiple sensors mounted on vehicles and to support mobile environmental and infrastructure monitoring. These systems can sense the environment at much finer fidelity and higher scale than static sensor networks, particularly over large areas, like highway networks (Hull et al. 2006). The CarTel nodes (vehicles) rely primarily on opportunistic wireless connectivity (e.g. Wi-Fi, Bluetooth) to access points in order to communicate with a central portal. Based on this work, Eriksson et al. (2008a) presented an improved system for delivering data to and from moving vehicles using open WiFi access points encountered opportunistically during travel. Like in the Pothole Patrol project, this system has been successfully evaluated in a real-world taxi test-bed. Extending the concepts described above, Rode et al. (2009) proposed integrated pothole detection and warning system that distributes collected data (spatially tagged potholes) to the participating vehicles assisting drivers in avoiding distresses.

In all cases, previous research showed that distributed vehicle networks are generally well suited for infrastructure monitoring and assessment (Hull et al. 2006; De Zoysa et al. 2007; Eriksson et al. 2008a&b) and are friendly to the environment when considering the additional emissions produced by dedicated assessment vehicles. However, all the approaches proposed so far and described above make use of sensor-fusion in terms of combining distress detection and positioning, but they are limited to elevation distresses, so they cannot detect and locate e.g. cracks. This is not sufficient for comprehensive condition surveys that include both surface and elevation distresses. Also, directly adopting laser based inspection solutions from dedicated inspection vehicles to common passenger vehicles is very difficult if not impossible, since laser-based systems come along with high initial costs and need for frequent maintenance and significant power for operation.

3. Methodology

Previous research has focused primarily on algorithmic accuracy, leading to accurate but often expensive solutions of limited applicability, typically implemented on dedicated vehicles. In practice, when faced with the pavement mileage that every agency (state, city, municipality, etc.) must maintain, the solution of using dedicated vehicles to monitor all pavement assets on a regular basis is not feasible. Regular evaluation can be made possible by gradually moving the monitoring task from the asset owners to the users (i.e. passenger vehicles) that drive on the roads daily. Under this paradigm, vision-based methods have the potential to help automate pavement distress detection and classification in a real-time environment (Tsai et al. 2010; Wang 2007). Besides, the sensor (camera) will soon be available on all vehicles because in response to the Cameron Gulbransen Kids Transportation Safety Act of 2007, the National Highway Traffic Safety Administration (NHTSA) has proposed all new cars to require rear-view cameras by 2014 (NHTSA 2010). The availability of these cameras on all vehicles creates a great opportunity to transform the future of pavement monitoring and assessment.

In the proposed framework, the rear-view camera of a passenger vehicle is replaced with a high-speed, high-definition, wide-angle camera that can tilt downwards during driving forward at daylight hours and is equipped with a strong LED light to compensate for occasional shadows. As shown in Figure 2, the video feed is continuously processed in real time 1) to directly detect frames with potential surface distresses and 2) to detect potential elevation distresses after sparse 3D reconstruction. Each time a set of frames with potential distresses is detected, the in-car GPS is used to add location information. The potential elevation distresses data is used to generate a dense 3D point cloud of the distress area. The resulting dense cloud and image data is then used for a more in-depth analysis to detect and classify distresses (cracks, rutting, and potholes) with state-of-the-art detection tools. The distress data (type, location, geometry, and appearance) are further processed to assess severity by comparing the measured attributes with those suggested in established assessment codes (e.g. FHWA 2003). Finally, findings from the network of cameras (the location and magnitude of distresses) are transmitted to Google Maps using established wireless protocols through the 3G/4G capability of the driver's cellular phone and the distresses are visualized for the public and all interested agencies (e.g. DOTs or Public Works departments). The severity and frequency of reporting a certain distress can then be used to assess its impact on the driving public as well as to feed in-car warning systems assisting upstream drivers in avoiding or minimizing the impact of severe distresses such as deep potholes.

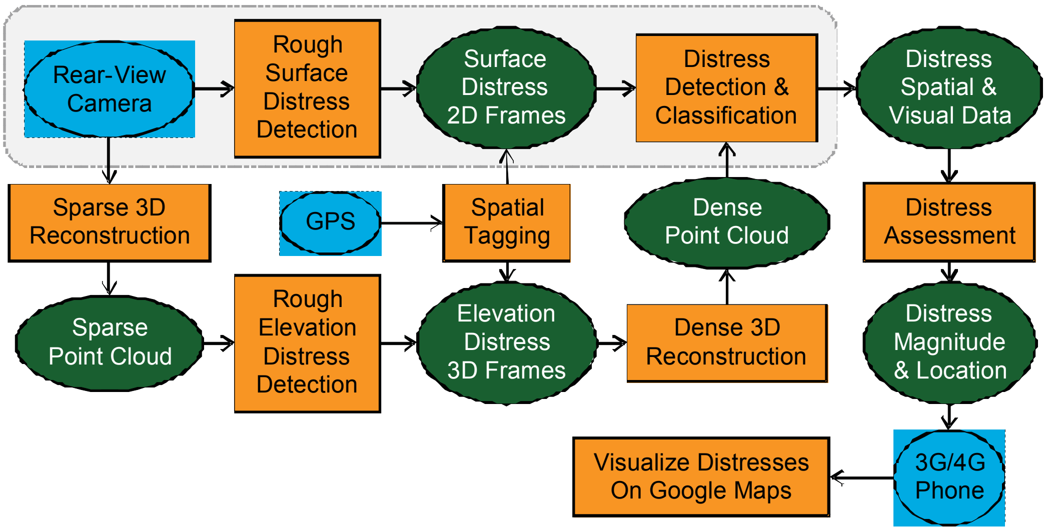

Fig. 2: Proposed framework emphasizing current efforts

As part of the framework presented above, Koch and Brilakis (2011a) presented a novel method for visual pothole detection in image frames. This method is based on the idea of creating specific pattern recognition models that take specific visual characteristics into account to detect certain defects. For a pothole, it was found that (1) it usually includes one or more shadows that are darker that the surrounding region, (2) its shape is approximately elliptical due to a perspective view, and (3) its surface texture is much coarser and grainer than the texture of the surrounding intact pavement. Based on these three distinctive visual characteristics a detection method was proposed (Fig. 3). Pavement images are first segmented into defect and non-defect regions using histogram shape-based thresholding. Then the geometric properties of a defect region are used to approximate the potential pothole shape through morphological thinning and elliptic regression. Subsequently, the texture inside a potential defect region is extracted and compared with the texture of non-defect pavement regions in order to determine if the region of interest represents an actual pothole.

Although experimental results validate this method, it is still limited to single images. Regarding rear-camera video feed it is computationally inefficient since the same pothole has to be re-detected and matched again and again. In addition, it is difficult to count individual potholes over a sequence of frames. For these reasons, the image-based method has been improved (Koch and Brilakis, 2011b). The enhanced pothole recognition method takes into account the sequence of frames from pavement videos. First, texture signatures for non-distress areas are incrementally updated using a number of preceding frames instead of a single frame. Thereby, the global pavement surface appearance is taken into account, which improves the pothole detection efficiency. Second, detected pothole regions are tracked in subsequent frames utilizing vision tracking algorithms. Once a pothole is detected in a video frame, the corresponding region is marked and tracked in the subsequent frames utilizing a selected vision tracking algorithm. In this way pothole tracking allows for convenient pothole counting in order to determine the magnitude of pothole distress in pavement videos.

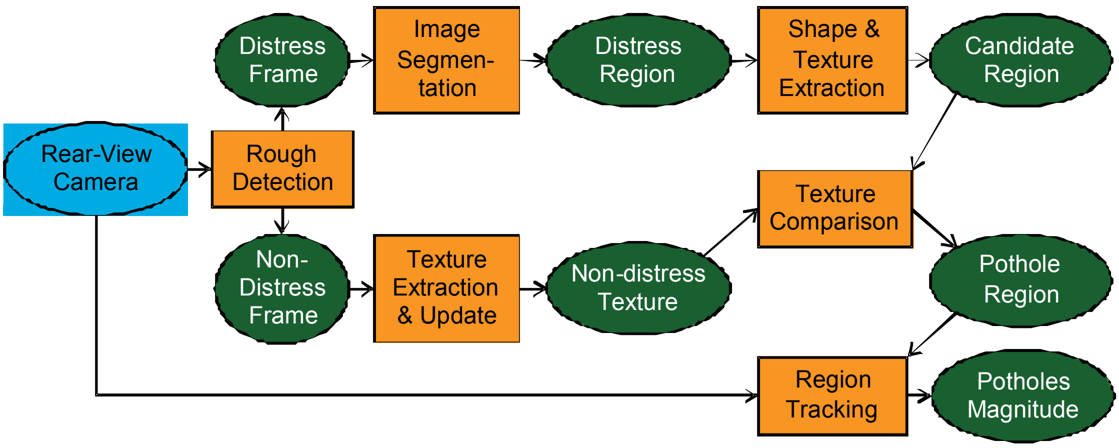

Fig. 3: Pothole distress detection methodology for pavement videos

4. Preliminary Results

In order to validate the current research efforts, a remote-controlled pavement assessment robot was used for data collection. This robot is equipped with a HP Elite Autofocus Webcam and a Viliv S5 Ultra Mobile PC (Intel Atom CPU, 1.33 GHz, 1GB RAM) (Fig. 3, top left). According to the framework proposed, the camera is installed at an altitude H of about 60 cm above the pavement surface, the height of a usual rear-view camera, and it is directed downwards at a 45° angle α. Using this robot a database of 120 single images and 39 pavement videos was collected around the Georgia Tech campus in order to train and test the effectiveness of the pothole recognition method. The image and video frame resolution is 640x480.

The presented pothole recognition method has been implemented in MATLAB version 7.11.0 (R2010b) utilizing the embedded Image Processing Toolbox. In the first step the image-based detection was validated obtaining an overall accuracy of 86% with precision of 82% and recall of 86%. Some examples of pothole detection in pavement images is shown in Fig. 3 (top right. In the next step this prototype has been extended by a vision tracker that tracks detected potholes. It was decided to use a robust kernel-based tracking algorithm proposed by Ross et al. (2008), because has been successfully tested and validated in outdoor environments where target objects undergo large appearance changes due to varying lighting conditions and object distances. Moreover, the object's appearance is incrementally learned throughout the tracking process without prior training. These features adequately meet the requirements of pothole tracking. In pavement videos the appearance of a pothole changes in scale, might change in illumination and is difficult to train due to the huge variety of potholes. Based on the 39 videos (in total 10180 frames) the overall recognition performance reached a precision of 75% and a recall of 84%. These measures validate the applicability of the pothole detection method as part of the proposed framework. Figure 3 (bottom) shows an example result for pothole detection in videos.

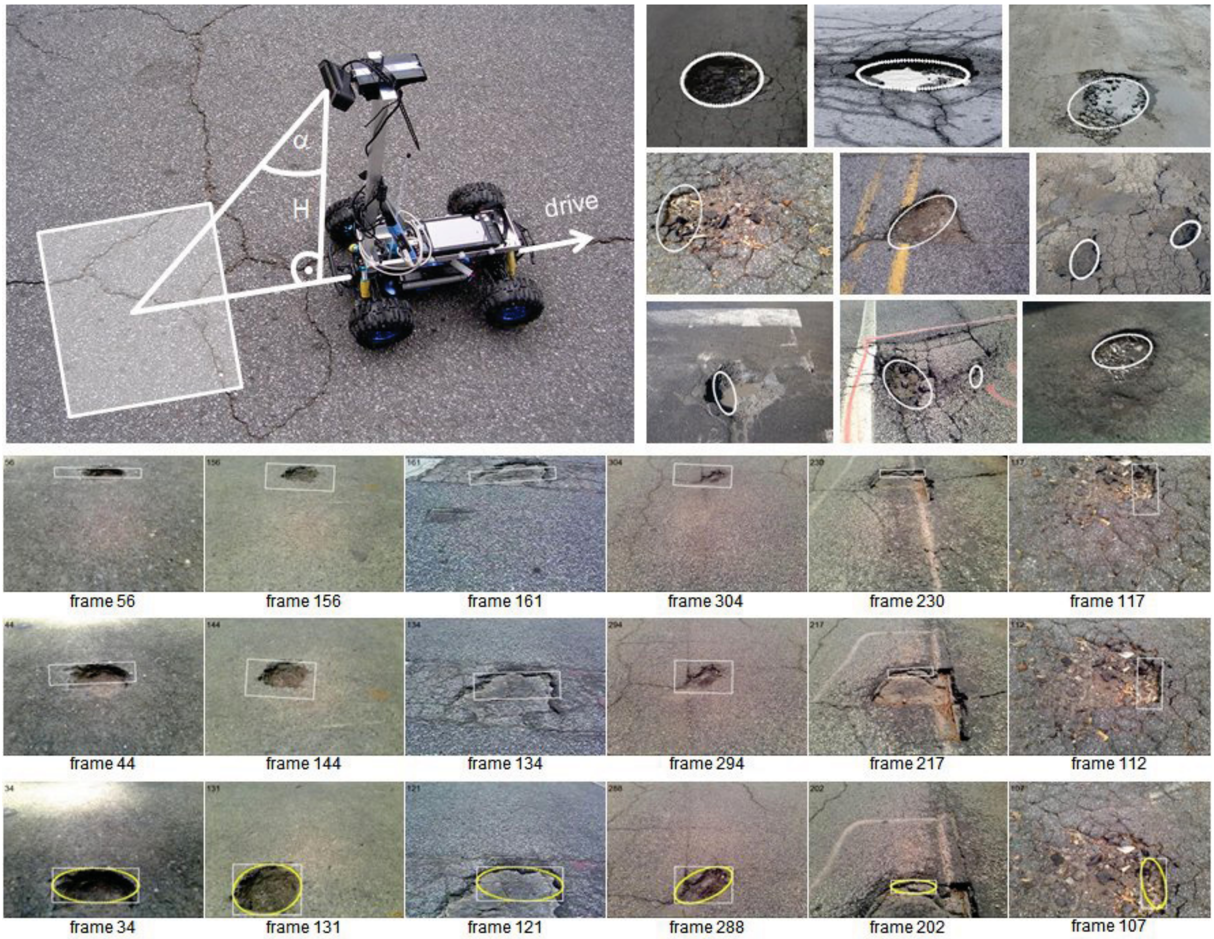

Fig. 4: Pavement robot (top left) and pothole detection results in images (top right) and in videos (bottom)

5. Conclusions and Future Work

Pavement condition assessment is primarily a manual and time-consuming activity. The manual nature of the task induces subjectivity and the experience of the inspectors alters the pavement rating. Moreover, only the first 50 feet of a mile of road is inspected to rate the pavement. Recently, efforts have been made to automate this laborious task. Several DOTs now use dedicated vehicles equipped with a variety of sensors such as cameras, lasers, and optical sensors. These vehicles automate the process of data collection but the process of data analysis is still manual. Research efforts have resulted in computer vision methods for crack detection and assessment, crack analysis and crack depth estimation. Besides cracks other distresses such as patching and raveling also have been successfully proposed. In addition to these, to overcome the limitations of 2D vision based methods, 3D reconstruction based methods for rutting, sags, and bumps have been proposed. 3D reconstruction based methods are either range sensor based or stereovision based. However, all these methods use dedicated vehicles for data collection. Due to the high costs involved in data collection, the assessment period for critical roads is one year and for smaller, local roads it is much longer or these roads are completely neglected. Various sensor fusion based approaches have shown that vehicular network is well suited for infrastructure assessment. Thus far sensor fusion has taken place only in terms of distress detection and localization and is limited to elevation distresses. This does not provide a comprehensive assessment of the pavement condition.

Therefore, this paper presented a concept framework in which the rear-view camera of cars is replaced with high-speed, high-definition cameras. The video feed collected from the camera is continuously processed to detect both surface and elevation distresses. Each pair of frames with potential surfaces is enhanced with location information from the in-car GPS. Then, the frames with potential elevation distresses are used for dense 3D reconstruction. Based on this reconstruction, the potential distresses are classified, analyzed, and their geometric properties can be retrieved. These properties are then compared with specific codes to evaluate the severity of the distress. Finally, this information is transmitted to Google Maps using the 3G/4G capability of the users phone.

As a first step in the validation of this framework, a pavement assessment robot was built. This robot was equipped with a HP Elite Autofocus Webcam and a Viliv S5 Ultra Mobile PC (Intel Atom CPU, 1.33 GHz, 1GB RAM). The webcam was installed at 60cm from the ground at an angle of 45° looking downward, a position similar to that of a rear-view camera in a car. Data collected from this robot was then used to validate a novel image and video based pothole detection method. The results for image based pothole detection have an accuracy of 86% with precision of 82% and recall of 86% whereas the results for video based pothole detection have a precision 75% and recall of 84%. These preliminary results signify that the proposed framework can be used as a sustainable solution for pavement condition assessment.

In the future work, existing methods for distress' detection will be compared and an accurate and appropriate method will be selected for each distress type. The selected methods will then be integrated into common software platform. 3D reconstruction aspect of the framework will be added and then the 2D and 3D data will be correlated to get accurate results. Once the framework is validated using the pavement assessment robot, data will be collected from a passenger vehicle to test and obtain total validation.

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THE APPLICATION OF MULTI-EULER DOMAIN IN BLAST LOADING SIMULATION

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ABSTRACT: *The collapse of World Trade Center (WTC) Towers in New York City in September 2001 raised a high interest level of protecting structures against blast loading. Traditionally, the blast-resistant design for structure was based on military experimental data and simple analytical models. However, all of these methods are only suitable for small structures and the approaches have limitations on modeling of certain material properties and complex blasting scenarios. Moreover, the costs of conducting a large scale experiment on a whole building or even a simple structure, as well as obtaining permission to conduct do it, make such experiment out of reach. In recent years, the fully coupled fluid-structure interaction model was developed via a coupled Euler-Lagrange computational algorithm, which can solve the materials and structures' responses under very fast and intense loading. Obviously, the Euler domain should be large enough to make sure explosive pressure can spread over the structure completely. However, this hydrocodes program was conventionally developed for weapon-scale phenomena, which means it is not practical for large structures, especially for those long-span bridges because of the element limitation and CPU speed. To solve this problem, a Multi-Euler (ME) domain method was proposed in this paper using the remapping technology of explicit finite element software. Good agreement between the solutions of traditional Single Euler (SE) domain and the Multi-Euler domain is achieved. The application of this method on a concrete-steel composite slab-on-girder bridge subjected to blast loading is presented. The results show the effectiveness of Multi-Euler domain method on reducing the element number and demonstrated its potential to solve the large-scale structure simulations under blast loading on personal computers.*

KEYWORDS: *Blast loads, Lagrange and Euler models, slab-on-girder bridge.*

1. Introduction

Over the past decades, the threat of terrorist attacks has drawn governments' attention. Conventionally, only essential government buildings and military structures take into consideration of the resistance design for structures under blast loading [1]. The terrorist attacks to bridges in California and New York have identified the urgent needs to evaluate the vulnerability of our transportation structures. Terrorist attacks are highly unpredictable events, and therefore it is hard to develop prevention measures. Comparing with the blast-resistant design for buildings, the limited information about blast-resistant design of bridges makes the problem even worse. Therefore, it is essential to investigate the behavior of bridges under blast loading and help to propose guidelines for blast-resistant design of bridges. Since experimental investigation of blast loading on bridges is nearly impossible to be conducted, several numerical approaches of air explosion simulation have been developed. The nonlinear explicit finite element analysis program AUTODYN [2] was used. However, existing commercial packages were conventionally developed for weapon-scale phenomena, which are not practical to apply them to solve large structures, especially for those long-span bridges because of the element limitation and CPU speed. To solve this problem, a Multi-Euler domain method is proposed in this paper to eliminate these constrains.

2. Blast Wave & Structural Analysis

2.1 Blast wave

Baker et al. stated that an explosion is "a phenomenon in which energy is released in a very fast and violent manner" [3]. The basic difference between blast loads and other dynamic loads is that the blast loads are moving pulse loads, loading different parts of the structure at different times, with varying magnitudes and durations, depending on the angle of incidence and distance. A blast wave can, broadly, be classified as air blast, underground blast and internal blast, depending on the point of blast being above or below the ground level, inside or outside of the structure.

The event of a simple explosion is defined by two important parameters, the bomb charge weight W, and the standoff distance R between the detonation point and the structure. An important parameter called scaled distance Z was proposed to represent the peak overpressure. This is related to the explosion parameters above. Typically the charge mass is measured in terms of TNT, and other types of explosives are converted to this material. It is obvious while the distance is increasing, the maximum pressure of the shock wave decreases. Here scaled distance Z is given by:

$$Z = \frac{R}{W^{1/3}} \qquad (1)$$

where R= distance from blast source;
W= mass of charge in terms of TNT

The pressure-time history of a blast wave in Fig.1 can be described by an exponential function such as the Friedlander equation [4]:

$$\Delta P(t) = \Delta P_{\max}(1 - \frac{t}{t_+})\exp\left\{-\frac{\alpha t}{t_+}\right\} \qquad (2)$$

Where ΔP max is the peak overpressure, t_+ is the duration of positive phase, α is the decay coefficient. From the equation above, it is obvious that blast loading is more sensitive to the distance R than the explosive weight W, which also demonstrates that the most effective way to minimize the damage is control the distance.

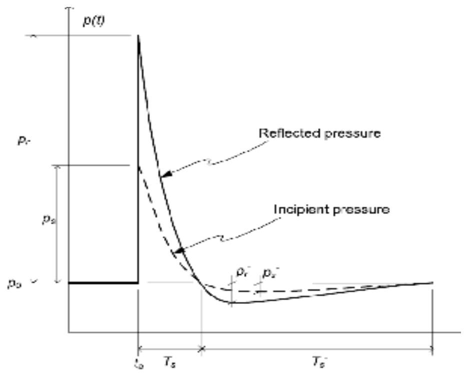


Fig. 1: Pressure-time profile for incipient and reflected blast wave

2.2 Numerical simulation

Because of the nature of blast loading and the nonlinearity associated with RC structures, nonlinear dynamic analysis was adopted to evaluate the structural response. Currently, there are two types of numerical models available for blasting simulation which are analytical model (decoupling approach) and coupled finite element model. Typical analytical models include the single/multi-degree-of-freedom (SDOF/MDOF) approach [5], empirical formulas and P-I diagram methods based on some military experimental data which simplify the blast loading as a triangle load case and apply it on the structures. All of these decoupling methods are only suitable for some simple structures and the approaches have some limitations on evaluating the structural damages and materials performance. Also, the above methods cannot predict the reflected pressure accurately either. In recent years, the fully coupled fluid-structure interaction finite element models were developed via a coupled Euler-Lagrange computational algorithm [6]. Furthermore, with the fast development of computer techniques, it has become possible to simulate the complex dynamic loading cases on personal computers. As one of the coupled methods, the Arbitrary Lagrange Euler (ALE) solver has been widely used for blasting event simulation because it could combine the medium and targets together and solve the problem through Euler-Lagrange mesh. This mesh method can predict the reflection of the blast waves accurately. Currently, many commercial finite element softwares have adopted this hydrocodes. Hydrocodes are computational mechanics tools that typically solve the response of both solid and fluid material under multi-situations, which based on a series of equations called equations of state (EOS). An EOS "is a relation between the density (or volume) and internal energy (or temperature) of the material associated with high pressure" [7]. By applying the principles of conservation of mass, momentum and energy, the material performance and structural response could be obtained in extraordinary conditions. Under blast loads, the dynamic equation of the structure can be defined as:

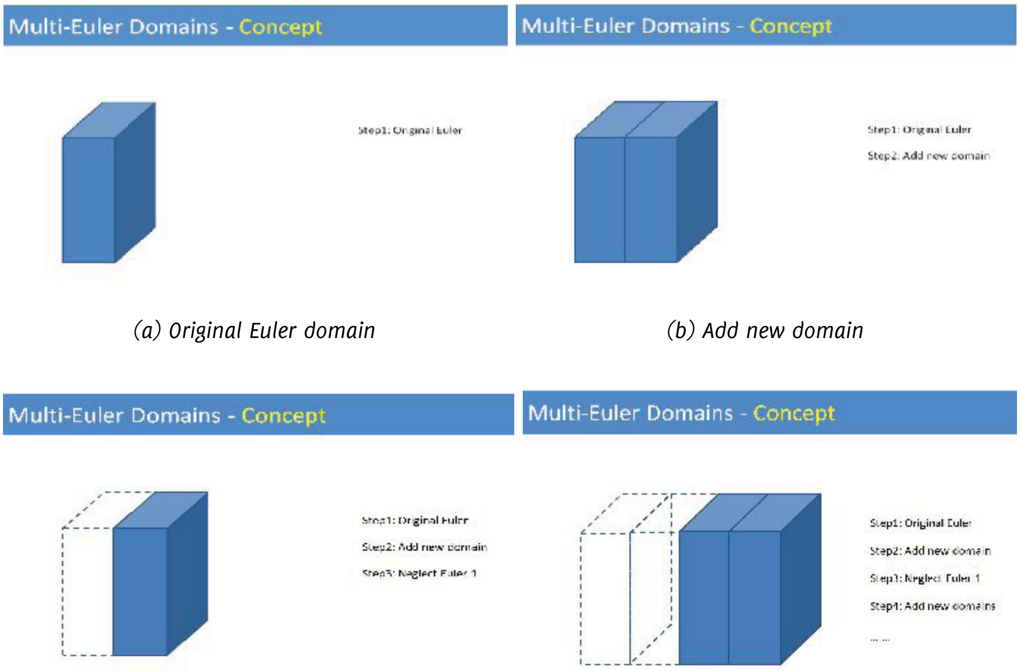
$$M\ddot{q} + C\dot{q} + f_{\text{int}} = f_{ext} \tag{3}$$

$$f_{\text{int}} = K \cdot q(t) \tag{4}$$

Where, , are the vectors of generalized displacement, velocities and acceleration. M, K and C are the mass, stiffness and damping matrices respectively, f_{int} is the vector of the internal resisting forces and f_{ext} is the vector of the external applied forces.

3. Multi-Euler Domain Method

In traditional ALE solver, the Euler domain was used to model the air range, which must be large enough to contain targets in blasting simulation [8]. As one of the basic hydrocode models, the Euler solver fix a grid over the space in where material flowing is possible. However, the main problems of Euler domain are the limitation of element numbers and the poor handling of geometry. The larger the structure is, the more elements and computer memory are required. To solve this problem, a Multi-Euler domain method was proposed in this paper. The proposed concept is shown in Fig.2.



(a) Original Euler domain *(b) Add new domain*

(c) Neglect initial domain *(d) Progressively delete and add new domains*

Fig. 2: The concept of Multi-Euler domain method

In the proposed Multi-Euler domain, the initial Euler domain in Fig.2(a) is modeled for the blasting remapping iput file [2]. With the propagation of the pressure, new Euler domain in Fig.2(b) needs to be inserted and connected with the previous ones. Subsequent Euler domains would be modeled until the pressure at the boundary of the previous Euler domains decreased to a level of less than 0.5MPa, which could be ignored in Fig.2(c). It is assumed that the air pressure lower than 0.5MPa has little influence on structures. In the similar fashion, new Euler domains were continuously introduced to replace the previous ineffective domains in Fig.2(d). This iterative process will stop until one of the following two criteria is met: either the maximum pressure in overall structure is lower than 0.5MPa or the increasing Euler domains have reached the end of the structure.

In this way, the peak pressure could be controlled at the certain air range with a number of specified Euler elements, which could avoid the participation of unnecessary elements. To prove the effectiveness of the method, a concrete-steel composite slab-on-girder bridge was analyzed for close detonation events. Proper mechanical properties of concrete and steel material under high strain rates were adopted. Also the verification of numerical simulation was presented comparing with experimental data.

4. Material Properties

The materials that are involved in this simulation were concrete, steel, air and explosive (C4 and TNT). During blast scenarios, materials are rapidly loaded by higher strain rates. It was found that the mechanical strength of materials during this rapid loading would be increased. The dynamic incremental factor (DIF) is defined as the ratio between the material property under rapid dynamic load and under static loading [9].

The steel girder is modeled by the Johnson and Cook material model [10], which is good to reflect the strength behavior of materials under large strain, high strain rates and high pressure. The density, bulk modulus and shear modulus are 7.83g/cm³, 159GPa, and 81.8GPa, respectively. Strain rate C is defined as 0.014 with yield stress of 792MPa.

The performance of concrete under blast loading has been tested by many researchers. In this study, a Johnson and Holmquist brittle damage model [11] was adopted because this model could simulate the concrete damage accurately based on the function of the plastic volumetric strain, equivalent plastic strain and pressure. In their model, they used the typical porous model and the Drucker-Prager model for EOS and the strength criterion, respectively. The hydro tensile limit of this model is -250kPa with 2.75g/cm³ density.

In the numerical model, air is always modeled by an ideal gas EOS. The flow model was assumed to be of constant entropy. The following equation of state was used for an ideal gas:

$$p = (\gamma - 1)\rho e \tag{6}$$

where p is the pressure and is a constant of 1.4. The air density and the internal energy e are 1.205kg/m³ and 2.068e5kJ/kg [9].

For the detonation material, the high explosives are normally modeled by the Jones-Wilkins-Lee (JWL) EOS, which is described by the equation below:

$$p = C_1\left(1 - \frac{\omega}{r_1 v}\right)e^{-r_1 v} + C_2\left(1 - \frac{\omega}{r_2 v}\right)e^{-r_2 v} + \frac{\omega e}{v} \tag{7}$$

Where p is the hydrostatic pressure, e is the specific internal energy, v is the specific volume, and C_1, r_1, C_2, r_2 and ω are constants related to the explosive characteristics. In this study, two kinds of high explosives were used: C-4 high explosive and traditional TNT high explosive. First, the C-4 explosive was used to verify the accuracy of coupled method comparing with the real experiment data, and then applied the TNT explosive in bridge simulation. The densities for C4 and TNT explosives are 1.601g/cm³ and 1.654g/cm³ [9].

5. Blast Wave Generation & Verification

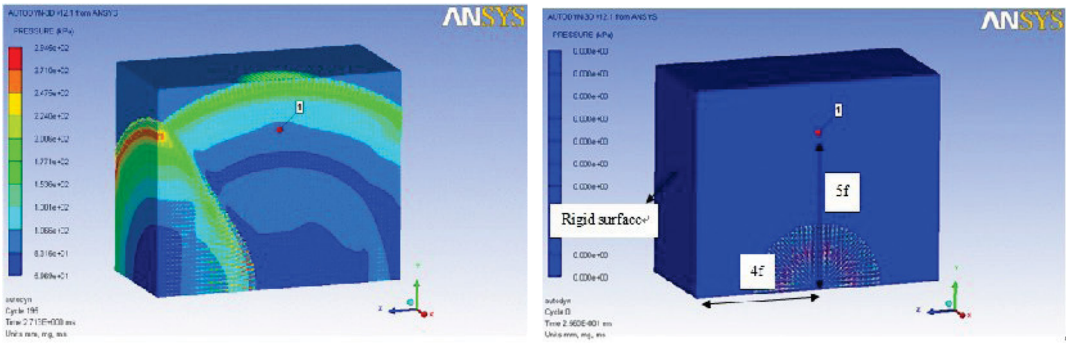
5.1 Generation of blast loading

It is quite complicated and difficult to study the dynamic responses of structures under blast loading because of the combining effect of material properties, structural behavior and detonation process. The current ALE method used to model blast phenomena still requires large computational resources and high CPU speed of computer. To solve this problem, the remapping technology [12] is developed to calculate the initiation and blast wave propagation. The analysis of the remapping technology is divided into two stages. First part includes the simulation of the explosion itself from the detonation and propagation of blast wave in air. Here a multi-material ALE solver in 1D with spherical symmetry is used. The second part is to import the previous remapping file into an Euler domain. Under this approach, the results of 1D can be copied directly into the 3D model while reducing the computational cost greatly.

5.2 Simulation verification

The simulation approach using coupled techniques and explicit finite element method should be verified for simple cases comparing with experimental data to ensure its validity. In this study, the experimental results of the C-4 high explosive [13] were adopted. The reflection of the shock wave by a rigid surface is conducted in this study.

In this example, the C-4 explosive charge is 4ft (121.6cm) away from a rigid surface. The gauge was set 5ft (152.4cm) above the detonation vertically to get both the incident and reflected pressure. The flow out boundary condition was assigned on the other sides. The dimension and detonation range are showing in Fig.3(a).



(b) Pressure propagation *(a) Dimension*

Fig. 3: Detonation in front of a rigid surface

In Fig.3(b), the incident pressure and reflected pressure from the rigid surface were presented. The experimental overpressure of 2.17bars occurs at t=2.0ms whereas the numerically predicted one at t=1.9ms is 2.23bars. The reflected pressures are 1.2bars and 1.30bars for experiment and simulation results, respectively. The comparison between experimental results and the simulation results are shown in Fig.4.

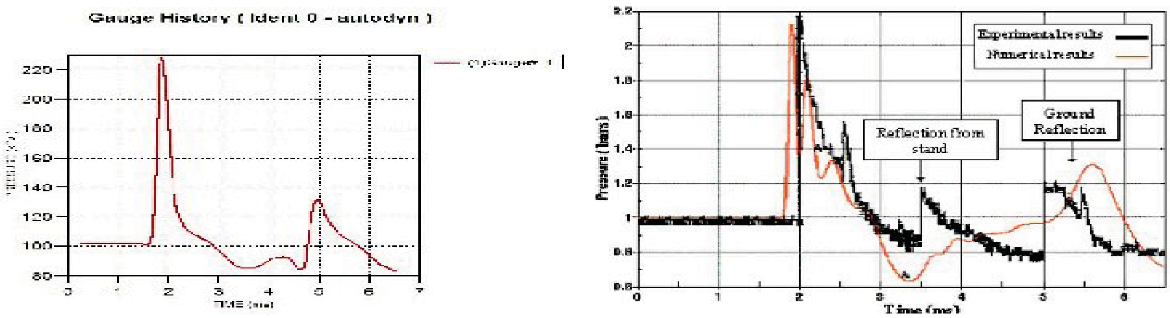


Fig. 4: Comparison of the experimental and numerical overpressure

It have been demonstrated that the magnitude, arrival time and duration of the pressure obtained from simulation compared reasonably with the experimental data.

6. Blast Analysis Model & Results

6.1 Bridge model

A single-span, two-lane composite slab-on-girder bridge is shown in Fig.5. The bridge has a span length of 24m, total width of 10m. The 225mm concrete slab contains two layers of reinforcement. Five steel girders are equally spaced at 2m apart, forming the slab overhang 1m on each side. To simplify the calculation, the reinforcedconcrete slab was modeled as homogenised elasto-plastic pure concrete with higher strength. Also the crossbeams were ignored.

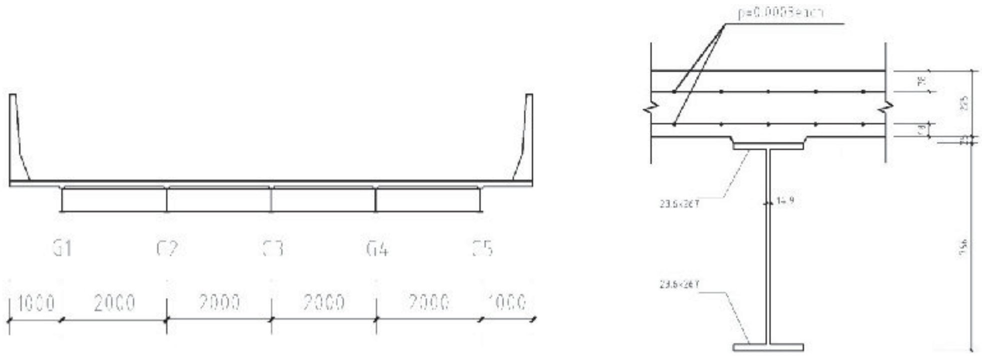


Fig. 5: Dimensions and cross section of the bridge

In the analysis, the gravity load was not considered in comparison with the high acceleration of blast loading. The bottom flange of the girder was considered fully restrained in the analytical model. All the parts of bridge were modeled by solid element. It was also assumed that concrete deck was rigidly connected to the steel girders. The whole bridge is solved with a Lagrange processor. The resulting finite element model is presented in Fig.6 by ANSYS mesh tools. It was further assumed that a car bomb detonation at a close distance in the middle of the bridge. The detonation took place at 1m above the deck surface with 100kg charge weight TNT high explosive.

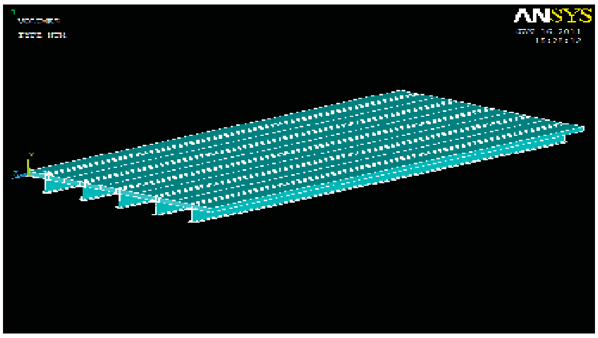


Fig. 6: Finite element model of bridge in ANSYS

6.2 Air range model

To verify the accuracy of the proposed Multi-Euler domain method, a conventional Single-Euler domain model was also built and analyzed under the same condition. For the Multi-Euler domain model, taking into account symmetry of the bridge, six sub-Euler domains were built along the longitudinal direction to cover the entire bridge. The dimension of each domain is 10m× 3m× 2m with 10cm mesh size. The computational time is 6.5ms.

6.3 Finite element analysis results

To reduce the computational work, a symmetric model was built for explicit dynamic analysis. Air pressure propagation during the 6ms after detonation is shown in Fig.7 and Fig.8 for Single-Euler domain and Multi-Euler domain, respectively.

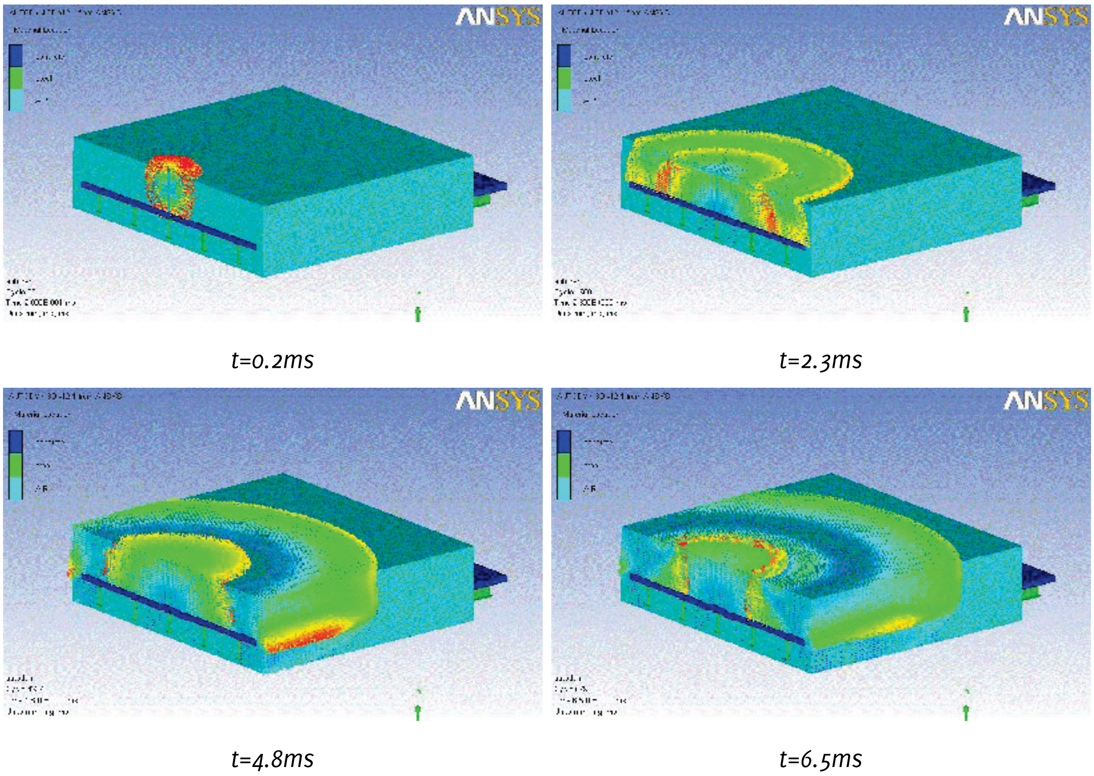


Fig. 7: Air pressure propagation for SE domain

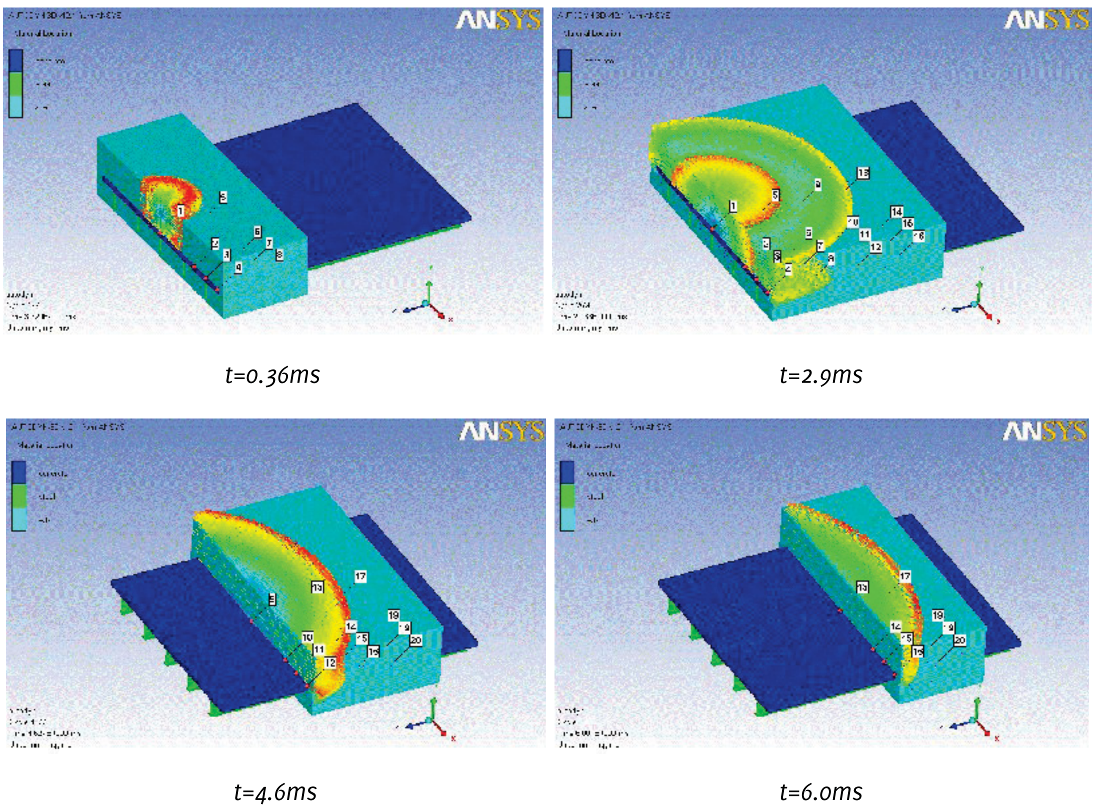


Fig. 8: Air pressure propagation for ME domain

Explicit dynamic analysis results showed that the same air pressure propagation process was obtained by using both the SE and ME domain methods. One of the most important factors in blasting simulation is the pressure time-history. To verify the accuracy, a list of gauges was set in air model as showed in Fig.9.

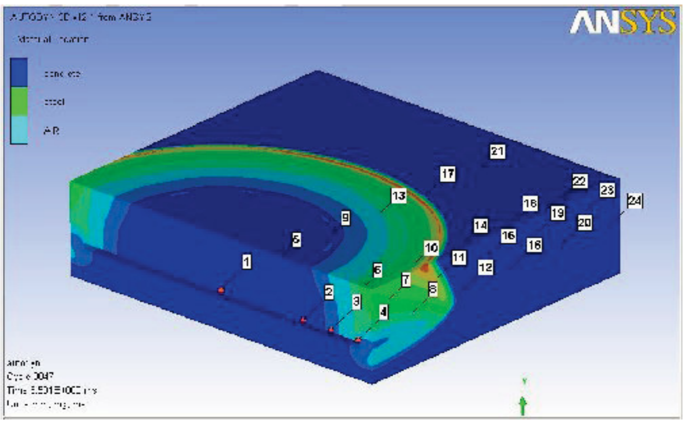
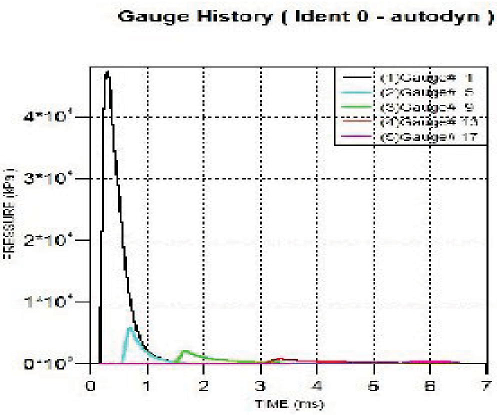
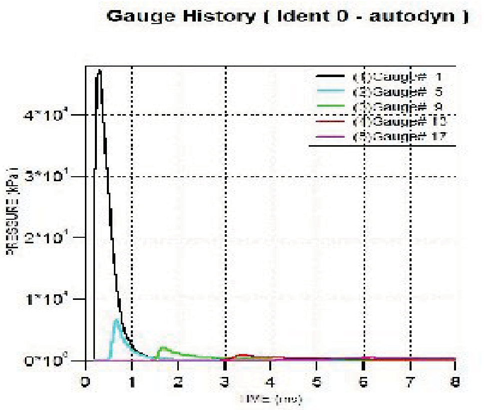


Fig. 9: Gauges in air range

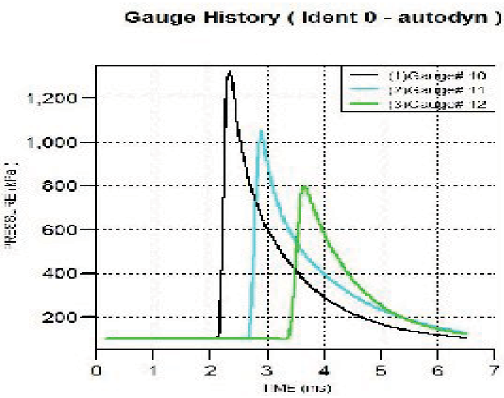
Gauges1,5,9,13,17,21 were along the bridge direction to obtain the peak overpressure. The three adjacent gauges at the boundary were used to check when pressures in Euler domain reached 0.5MPa which could be neglected.



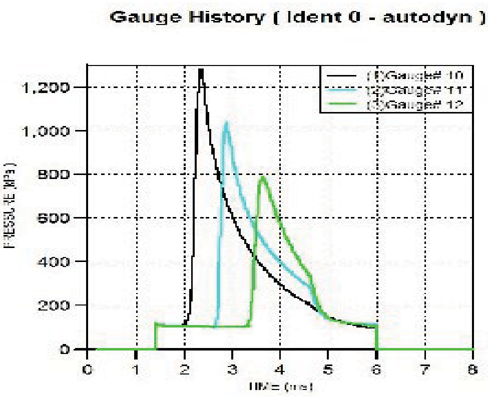
(a)SE Domain



(b)ME Domain



(c)SE Domain

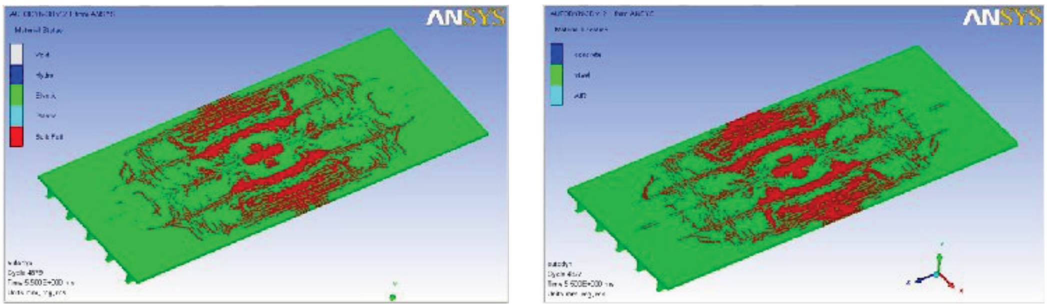


(d)ME Domain

Fig. 10: Pressure time-history on gauges

The figures above showed the same time-history of two Euler domain simulations. The peak pressure of 4.8×10^4 kPa was obtained from both models in Fig.10(a) and Fig.10(b). The discontinuous curves in Fig.10(d) showed that the 2nd Euler domain in ME model was ignored at t=4.6ms, the pressure started to decrease rapidly.

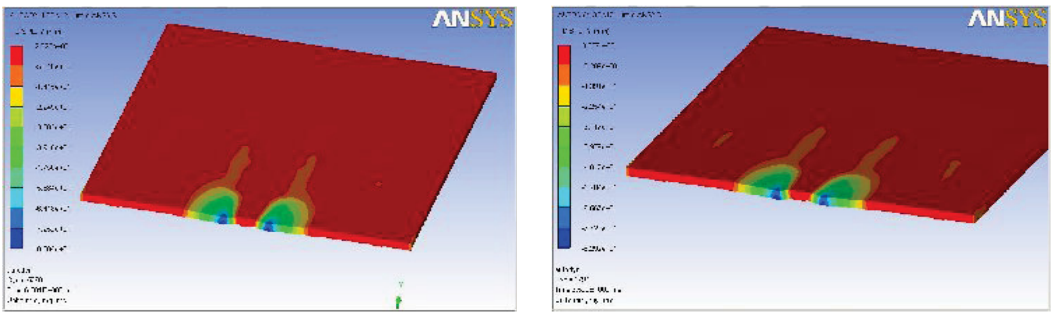
Fig.11. shows the bridge damage conditions at t=5.5ms, the red parts represent the bulk failure based on the compressive and tensile strength limits. The concrete deck damage pattern obtained from the ME model is the exactly same as SE model in near field of detonation, but slightly extended in far field, which could be explained by that ME model are more effective in spreading air pressure along the bridge.



SE domain *ME domain*

Fig. 11: Damage on the bridge deck

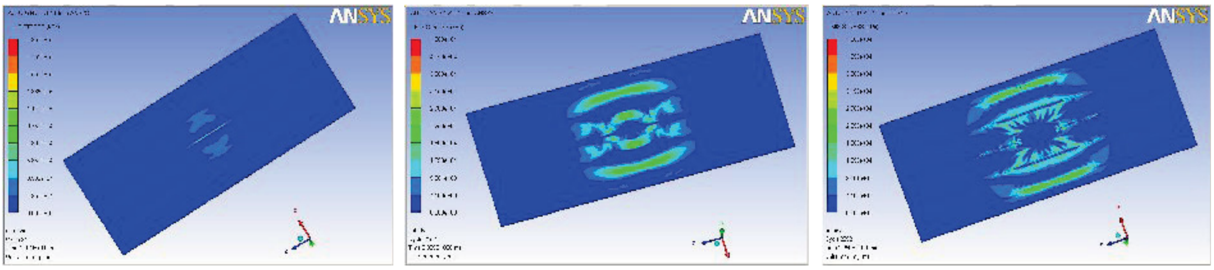
Since the bottom flange of the girder was fully restrained, the maximum vertical displacements appeared in the middle of bridge, which are 80.85mm and 82.92mm, respectively from SE and ME models in Fig.12. Similar performance was observed for the bridge girder under blasting load, the maximum deflection appears at the edge of top flange in the middle girder, which are 14.70mm and 16.08mm for SE and ME model respectively.



SE domain *ME domain*

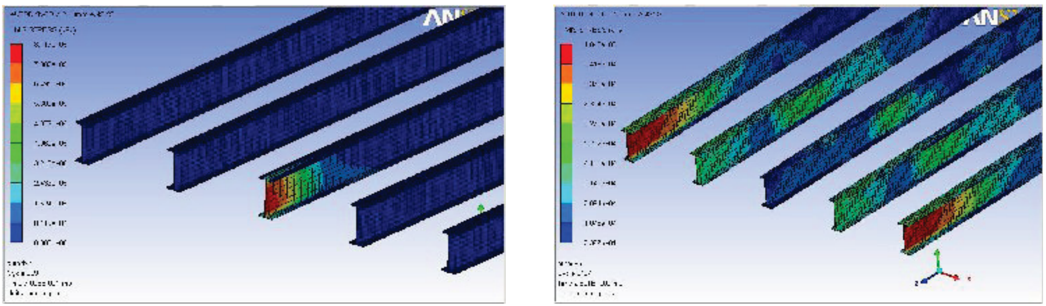
Fig. 12: Comparison of Y-disp. on deck

The Von Mises stress distribution on bridge is shown in Fig.13. For the sake of visualization of concrete deck, the steel girders are removed in Fig.13(a).



t=1.2ms *top view (t=2.96ms)* *bottom view(t=2.96ms)*

(a) Von Mises stress on deck for ME domain



t=0.9ms *t=2.8ms*

(b) Von Mises stress on steel girder for ME domain

Fig. 13: Stress distribution in bridge

The peak Von Mises stresses appeared at the time when first shock came. With the pressure propagation, the second peak values were obtained around t=3ms due to bridge vibration. Table.1 lists the stress comparison:

Table.1: Stress field comparison

		SE Domain (kPa)	ME Domain (kPa)	Difference
Deck	t=1.2ms	195000	195000	0.00%
	t=3.1ms	43540	45000	3.35%
Girder	t=0.9ms	811500	811900	0.05%
	t=2.8ms	105800	104600	-1.13%

The bridge continues to vibrate until the solution time is reached. The Multi-Euler domain method used in this study is more effective for the large structures, such as long-span bridges and high-rise building.

7. Conclusions

The numerical simulation and analysis of the structural damage of a concrete-steel composite slab-on-girder bridge subjected to blast loading is presented. A new Multi-Euler domain method was developed to solve large, complex structural responses under blast loading. The excellent agreements of peak overpressure and reflected pressure between numerical simulation and the experimental data ensure the reliability of computational method and simulation approach. Findings obtained from the Multi-Euler domain method are as follow:

- Reliability: Results are reasonable and valid in comparison with the traditional Single-Euler domain method
- Convenience: The Multi-Euler domain method is easy to mesh the air mass into elements in Euler domains with varying size
- Efficiency: The approach could re^duce the element numbers significantly as well as shortening the cycling time of every single Euler domain, which makes it possible to solve large structural simulation on personal computers.

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BIM-BASED LEAN-AGILE SUPPLY CHAIN FOR INDUSTRIALIZED HOUSING

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ABSTRACT: *Housing builders in Sweden have been moving from on-site production to industrialization. From 1990 to 2002, approximately 74% single-family detached houses in Sweden are prefabricated by industrialized housing builders. To fulfill the benefits of industrialization, the design specifications have to be worked out from a list of predefined standardized components and elements. On the other hand, the requirements of client (diversity, cost and delivery time) make design specification process seems to be complex and paradoxical situation, which may lead to the ad-hoc design customization and slow response to potential client's enquiry. This research therefore presents a BIM-based configuration design, in which lean-agile supply chain is used to balance and manage the trade-off between builders and clients, standardization and customization. Furthermore, integrating discrete event simulation (DES) with building information model (BIM) enables an enriched information model including cost and delivery time. The research argues that the industrialized housing is the systematic trade-off and balancing the values of all stakeholders and BIM-based lean-agile industrialized configuration design provides an effective trade-off platform.*

KEYWORDS: *BIM, lean-agile, industrialized housing, DES*

1. Introduction

Industrialization is a business strategy that transforms the traditional on-site construction process into a manufacturing and assembly process in order to reduce cost, time, and improve the quality . Housing builders in Sweden have been moving from on-site production to industrialization . From 1990 to 2002, approximately 74% single-family detached houses in Sweden are prefabricated by industrialized housing builders . The industrialized house building is reported to improve productivity, cost, delivery time, quality . To fulfill the benefits of industrialization, the design specifications have to be worked out from a list of predefined standardized components and elements. However, a serious obstacle for industrialized housing is to configure the housing according to client's requirements (diversity, cost and delivery time) while to consider the constraints imposed by the industrialized production systems. Designing completely according to the customer's requirements regardless of the technical constraints of industrialized production system often leads to ad-hoc customization that can be hard to fulfill for the industrialized builder . Consequently, it loses the benefits of industrialization. On the other hand, providing standardized housings to marketplace has been criticized for reducing the possibilities of customization to satisfy the diversity . Hence, industrialized housing needs to balance and coordinate the interests and possible conflicts between different stakeholders .

This research therefore presents a BIM-based configuration design, in which lean-agile supply chain is used to balance and manage the trade-off between builders and clients, standardization and customization. Furthermore, integrating DES with BIM enables an enrich information model including cost and delivery time, which provides a quick response to potential client's enquiry.

2. Stakeholders' value

Malmgren et. al. defined four product views relevant for industrialized building systems: customer, engineering, production and site assembly view. These views show the product breakdown from the different stakeholders' perspective. Figure 1 shows the flow of information and constraints.

- The customer view contains the clients functional requirements and is created by the architect or sales department
- The engineering view is transformed from the customer view and detailed into building parts to be manufactured
- The production view contains the necessary information needed to pre-manufacture the building parts. It contains information relevant for the supply chain and the factory production units.
- The assembly view contains information on how to assemble the pre-manufactured building parts

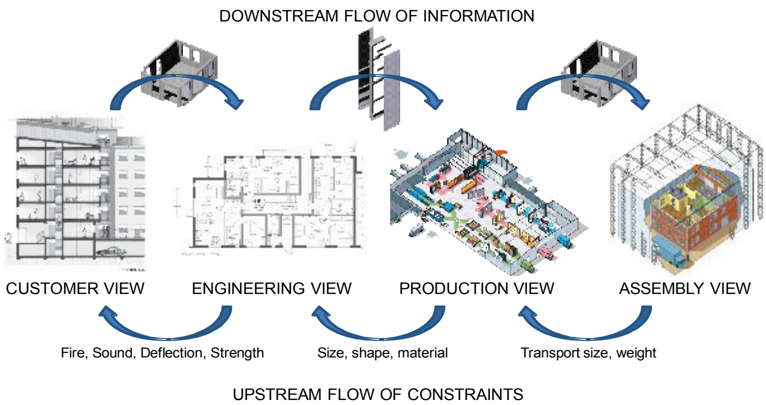

Fig. 1: Information Flow between the Different Views (Olofsson et al., 2010)

Each view represents the interest of customer, engineering, production and assembly respectively. Usually, it is common practice for companies to "throw over the wall" which means transfer information downstream the value chain rather than transferring information, rules and constraints upstream the value chain. When the manufacturing and engineering department received order that is difficult or impossible to fulfill for technical constraints, it is often too late, expensive and troublesome to correct it. Thus, the demands for standardization from a production point of view need to be balanced by the demand for customization. However, little attention has been devoted to transfer information upstream from manufacturing and engineering to the customer view .

3. Lean-agile supply chain

Lean paradigm has emerged as one of the sources to achieve competitive advantages in construction industry. The winner criterion of lean paradigm is cost reduction by eliminating of wastes in production system, while agile production emphasizes the response to fluctuating market demands. Naylor et al. proposed the concept of 'leagile', combining lean and agile paradigms to provide an optimal balance between responding to volatile demands downstream while providing stable and predictable production environment upstream from the de-coupling point. The de-coupling point separates parts of the production process geared towards satisfying clients' orders from the parts based on planning . That is, the de-coupling point links lean and agile processes together.

It is argued that housing construction offers the closest analogy to lean production and matches that of auto production . Simultaneously, in order to quickly response to volatile market demands, construction companies increasing embrace agile paradigm to enhance service level. The adaptability to synchronize with volatile marketplace ensures the survival of industrialized construction. Naim and Barlow indicated the potential application of leagile to the housing industry and developed a rich pictorial representation of the engineered supply chain. Nevertheless, the research has been mainly at the strategic level, a major limitation is the lack of how to build leagile supply chain .

Figure 2 shows the processes of Swedish industrialized housing which based on the complete number of Swedish companies using industrialized Timber Volume Element (TVE) housing production. Those companies manufacture building components, or entire houses in factory, reduce activities at the construction site to the assembly of parts . With the moving of de-coupling point, the factory prefabrication and on-site production is reallocated : with shifts in the de-coupling point upstream of the production system, the agile process increases, while moving it downstream of the production system increases leanness.

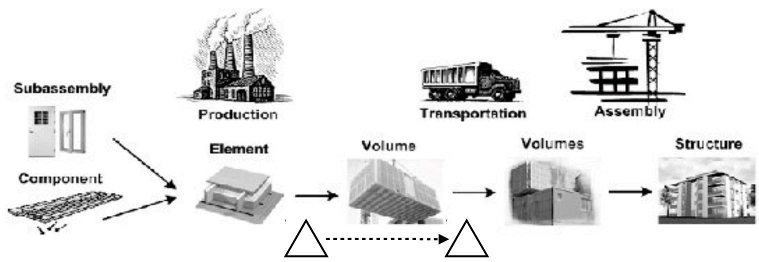

Fig. 2: Swedish industrialized housing

4. DES in construction

DES has been proven to be an effective technique in predicting productivity and evaluating the behaviours of system . It has been used in Construction Engineering and Management (CEM) research community since the development of CYCLic Operations Network (CYCLONE) . After the introduction of CYCLONE, there have been many construction simulation programs developed, such as UM CYCLONE , STROBOSCOPE , ABC , Simphony.net , RiSim and SDESA . Construction simulation is the science of developing and experimenting with computer-based modelling of construction systems to analyse their underlying behaviours . It is a quantitative analysis methodology that the behaviours of system can be quantitatively evaluated and redesigned until it has achieved expected performance.

Vitascope , which integrates DES with 3D visualization enable the modeller to visualize simulated processes in smooth, continuous, 3D virtual worlds. Such 3D visualization provides valuable and accurate insight into the DES model and facilitates simulation model verification and validation. For instance, a system of tower crane operations integrating 3D visualization with DES was built to effectively communicate and understand simulated construction operations, thus improve the credibility and accessibility of simulation model . The relationships and framework for integrating lean theory and simulation methodologies has also discussed in construction simulation . In general, lean thinking provides a structured format in which processes can be re-designed , and DES offers a methodology to re-engineer the construction operation under lean theory . Hence, this research adopts visualization-simulation DES model and integrate such model with lean-agile thinking.

5. BIM-based lean-agile supply chain

To cope with customer variety, companies need to balance those customer desires with operational reliability in a flexible manner . Product configuration is proposed to meet customer specifications with engineering and physical constraints . Product configuration is described as an effective way of structuring products composed of standardized parts but also as a method of presenting products to clients. Additionally, products structured in a product platform become the company common view of the product range that can be shared by sales, design and production departments. In the work with product customization many industries have developed methods to design product platforms . These platforms can be configured either by adding, removing, or substituting modules to the platform or by scaling the platform in one or many direction to target a special market . Jensen (2010) developed an engineering configurator demonstrator of the floor slab module in Tyréns wooden building system based on requirements, as shown in Figure 3. The building system modules can be imported in Revit as a family in the customer view. The floor slab family consists of four different widths “600, 1200, 1800, 2400”, where the length parameter is parametric within the module limits and set with Revit accuracy scale “Course, medium, fine” using a grid of 150 mm. A distance parameter between modules was defined representing the interface when connecting the floor slab to walls. The downstream flow from customer to the engineering view was demonstrated using XML export/import mechanism but could have been realized using IFC.

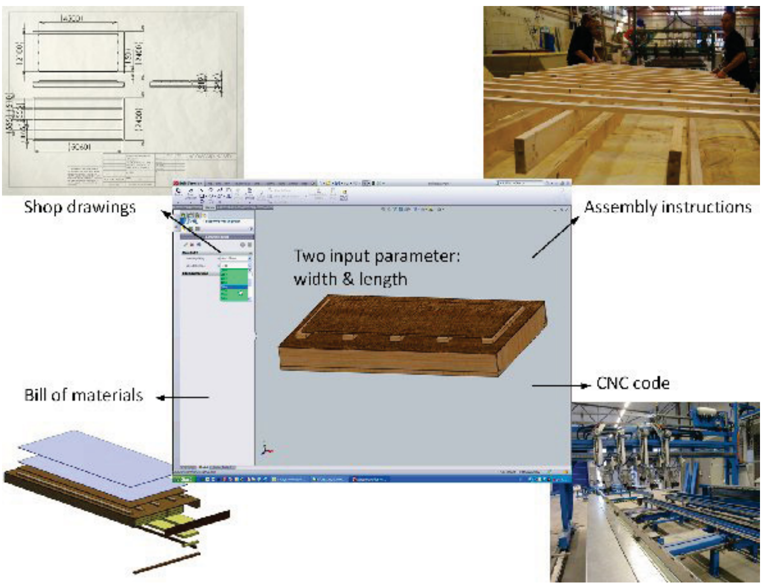

Fig. 3: The implemented floor slab configuration demonstrator, Jensen (2010)

Building information modeling (BIM) defines as “a computable representation of all the physical and functional characteristics of a building and its related project/lifecycle information” for the building stakeholders to use and maintain throughout the lifecycle of a building . BIM presents as objects (walls, columns, windows, doors, etc.) with attributes and relationships between building elements . BIM includes not only the geometry information of a CAD object but also the information that supports the activities involving the objects and their relationships with the other objects . Figure 4 presents BIM-based lean-agile supply chain, in which the whole industrialized housing is organized according to lean-agile supply chain. This research builds hierarchical Discrete Event Simulation (DES) model for industrialized building processes. The lower level DES model simulates the detailed operational processes for selected components. Extracting data from lower level DES, the higher DES model simulates the performances (cost and delivery time) of lean-agile supply chain for industrialized housing, which are exchanged through BIM platform.

Figure 5 describes the flowchart of BIM-based lean-agile supply chain. Sales and customers are co-designers of industrialized housing. A customized house can only be developed if the customer is involved in the housing specification process. Sales and customers together decide the dimensions, materials, colour etc. of every selected component from a list of predefined components. After confirming the selected components, the delivery time and cost are simulated by encapsulating specifications sub model in each component. The component is represented by sets of attributes and defined values, such as list of operations, resource required, duration, sequences and order number. The developed simulation model intelligently responses and simulates the production of components according to above specifications of components and factory constraints. Simultaneously, the visualization model provides a transparent communication platform to customers, sales and builders. If conflicts are observed in the visualization platform or customers disagree with the delivery time and cost, this cycle process perform again until all stakeholders are satisfied and agreed with the customized housing design. And then, the order is released. Accordingly, such framework ensures a consistent and effective information communication (upstream and downstream) between all stakeholders.

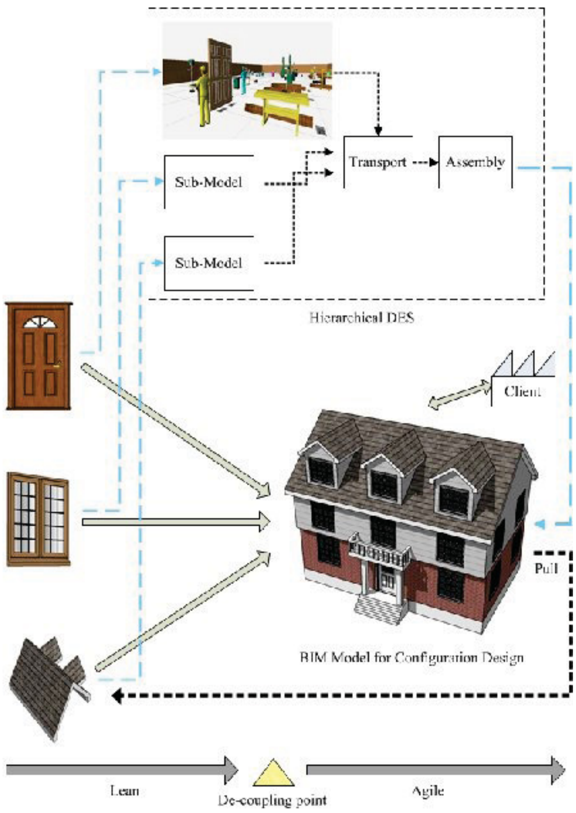

Fig. 4: BIM-based lean-agile supply chain

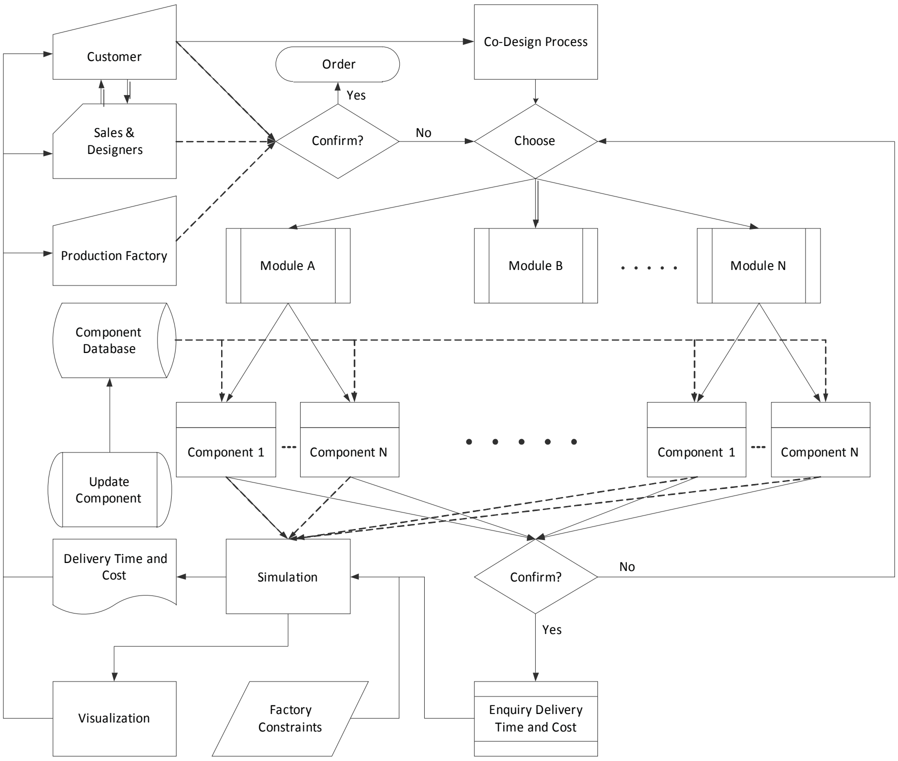

Fig. 5: Flowchart of BIM-based lean-agile supply chain

6. Discussion

Making a better match between buildings and clients' needs will influence the clients' satisfaction and thus leading to a higher level of durability of the building . This research argues that the value of all stakeholders should be considered and balanced in industrialized housing. The industrialized housing is a balance between flexibility of adapting to customer requirements and efficiency in design and production. Design automation in the engineering view, can be implemented in parametric tools and product configurators normally used by the mechanical industry. The effective trade-off among all stakeholders will minimize the risk for ad-hoc design solution propagating downstream to production and assembly on-site. This will also speed-up the design process and enables production to be automated and industrialized.

For the fragments in industrialized housing, the information and communicating technology (ICT) provides alternative solution to it. This research therefore presents a BIM-based configuration design, in which lean-agile supply chain is used to balance and manage the trade-off between builders and clients, standardization and customization. BIM lie at the core that it is used not only to detect the design conflicts and mistakes, also to be value balance platform providing enriched information to all stakeholders.

Value is only significant if, for example, a product meets customer demands at a specific time and a specific price . Integrating DES with BIM enables an enriched information model including cost and delivery time, which make an agile response to potential clients' requirements to be possible.

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A GAME-LIKE VIRTUAL REALITY CONSTRUCTION SITE SIMULATOR FOR NON-COLLOCATED COLLABORATION

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ABSTRACT: *Success of Architecture, Engineering, and Construction (AEC) projects are often highly dependent upon the type, level and quality of the communication exchange between the various disciplines involved in the design and implementation phases. Recent innovation in Virtual Reality (VR) technologies and AEC decision- support toolkits have now matured, enabling tele-presence engagement to occur through collaborative environments. Several opportunities are now available, including significantly improved immersive interactivity with haptic support that can enhance users' engagement and interaction. This study builds on previous studies in this area, with specific emphasis on supporting the decision-making process at the construction stages. This paper presents capabilities of the developed Game-Like VR Construction Site Simulator (GVRSS) through three core phases: 1) Need Analysis and exploring existing systems through a series of focus groups and structured interviews with 17 AEC experts, 2) System Development using Unified Software Development Process, 3) examination of the impacts of utilising GVRSS on AEC actors using the Charrette Test Methodology. This study supports a novel approach of applying Game Theory to non-collocated design teams using Game-Like VR environments blended to Social Sciences Theory (social rules) and Behavioural Science Theory (decision science/communication science). In terms of knowledge contribution, the study identified the causal drivers and impacts associated with enhanced decision-making in non-collocated AEC teams at the construction stage. It develops an insight and understanding about virtual collaborative workspaces, especially though new social interactions (and decision-making criteria) generated based on Game Theory. This study is the first of the kind in measuring and evaluating actor involvement and positioning. It also reveals a new insight into organisational behaviour (within an AEC setting), along with social constructs that contributes to the wider understanding of Management Theory (organisational setting).*

KEYWORDS: *Virtual Reality, Construction Management, Game Theory, Collaborative Interfaces, Data Communication.*

1. Introduction

The nature and complexity of communication mechanisms within the Architecture, Engineering, and Construction (AEC) projects has changed significantly over the last ten years, especially the modus operandi and integration with core business operations. This has been reflected through the increased prevalence, use, and deployment of web-based project collaboration technologies and project extranets. Within the AEC sector, Information and Communications Technology (ICT) has revolutionised production and design (Cera et al., 2002), which has led to dramatic changes in terms of labour and skills (Fruchter, 1998). However, it is also important to acknowledge that the capabilities of such applications (and implementation thereof) in predicting the cost and performance of optimal design proposals (Petric et al, 2002) should enable design engineers to compare the quality of any one tentative solution against the quality of previous solutions. This was further reinforced by Goulding et al. (2007), regarding the ability to experiment and experience decisions in a *'cyber-safe'* environment in order to mitigate or reduce risks prior to construction. It is therefore crucial for the AEC industry to employ cutting-edge ICT technologies to issues related to organisational management and decision making (Friedman, 2005). Furthermore, whilst advocates note that these have helped to resolve some of the aforementioned challenges, Alshawi and Ingirige (2003) and Ibrahim and Pour Rahimian (2010) noted that project teams are still facing real and signification problems and challenges regarding heterogeneous systems faced by project teams using project extranets. In this essence, the problem here is that the industry is experiencing confusion as to how to manage project information in order to support decision-making processes. This is the point where Fruchter (2004) suggested the digital integration of the whole data creation, retrieval, and management system within building industry in order to prevent tacit knowledge loss and miscommunication among various parties from different disciplines. In this respect, recent innovation in Virtual Reality (VR) technologies and AEC decision-support toolkits have now matured, enabling tele-presence engagement to occur through integrated collaborative environments. Several opportunities are now available, including significantly improved immersive interactivity with haptic support that can enhance users' engagement and interaction.

Employing cutting edge ICT tools is also expected to leverage training systems within the AEC sector (Fruchter, 1998) as the implementation of effective training could make impact on the whole industry by addressing and fulfilling the needs of the different stakeholders in the industry. In this respect, advanced ICT systems are expected to address the shortcomings of 'typical' learning models that often provide the trainees with only general instructions (Laird, 2003) and issues associated with unaffordable costs of the 'traditional' on -the-job trainings (Clarke and Wall, 1998). Therefore, new ICT advancements incorporated innovative proactive experiential learning approaches which link theory with practical experience, using Virtual Reality interactive learning environments (Alshawi et al., 2007). This research extends the findings of previous studies in this area, with specific emphasis on supporting the decision-making process at the construction stages. The study provides a novel approach of applying Game Theory to non-collocated design teams using Game-Like VR environments blended to Social Sciences Theory (social rules) and Behavioural Science Theory (Decision Science/Communication Science). In essence, the aim of this study was to provide a flexible, interactive, safe learning environment for practicing new working conditions with respect to offsite production (OSP) in general, and Open Building Manufacturing (OBM) in particular; without the do-or-die consequences often faced on real construction projects. Hence, a VR interactive learning environment was sought which builds upon the multi-disciplinary practice-based training concept (Alshawi et al., 2007). In this context, the prototype aimed to enable disparate stakeholders, with different professional specialisations, to be exposed to the various aspects of OSP concepts. This approach was adopted in order to help overcome the problem of 'compartmentation' of knowledge (Mole, 2003). Furthermore, the prototype had to be flexible enough to allow any-time-any-place learning, so as not to be constrained to a particular place or time for learning to take place. This paper presents capabilities of the developed Game-Like VR Construction Site Simulator (GVRSS) through three core phases: 1) Need Analysis and exploring existing systems through a series of focus groups and structured interviews with 17 AEC experts, 2) System Development using Unified Software Development Process (Jacobson et al., 1999), 3) examination of the impacts of utilising GVRSS on AEC actors employing Charrette Test Methodology (Clayton et al., 1998).

2. Study Background

VR has been defined as a 3D computer-generated alternative environment to be immersed in, for navigating around and interacting with (Briggs, 1996), or as a component of communication taking place in a 'synthetic' space, which embeds human as its integral part (Regenbrecht and Donath, 1996). The definitions of VR systems usually includes a computer capable of real-time animation, controlled by a set of wired gloves and a position tracker, and using a head-mounted stereoscopic display as visual output. For instance, Regenbrecht and Donath (1996) defined the tangible components of VR as a congruent set of hardware and software, with actors within a three-dimensional or multi-dimensional input/output space, where actors can interact with other autonomous objects, in real time. VR has also been defined as a simulated world, which comprises of some computer-generated images conceived via head mounted eye goggles and wired clothing – thereby enabling the end users to interact in a realistic three-dimensional situation (Yoh, 2001).

2.1 Virtual Reality in Architecture, Engineering, and Construction

Over the last 30 years, ICT systems have matured and enabled construction organisations to fundamentally restructure and enhance their core business functions. Sampaio and Henriques (2008) asserted that the main objective of using ICT in construction field is supporting management of digital data, namely to convert, store, protect, process, transmit, and securely retrieve datasets. They acknowledge the commencement of VR techniques as an important stepping stone for data integration in construction design and management as they are capable of holding and presenting the whole information about buildings (e.g. size, material, spatial relationships, mechanical and electrical utilities, and etc) through a single output. Similarly, Zheng et al. (2006) proposed the use of VR to reduce time and costs in product development and to enhance quality and flexibility for providing continuous computer support during development lifecycle.

Early studies that incorporated VR into the design profession used it as an advanced visualisation medium. Since as early as 1990, VR has been widely used in the AEC industry as it forms a natural medium for building design by providing 3D models, which can be manipulated in real-time and used collaboratively to explore different stages of the construction process (Whyte et al., 1998). It has also been used as a design application to provide collaborative visualisation for improving construction processes (Bouchlaghem et al., 2005). However, expectations of VR have changed during the current decade. According to Sampaio & Henriques (2008), it is increasingly important to incorporate VR 3D visualisation and decision support systems with interactive interfaces in order to perform real-time interactive visual exploration tasks. This thinking supports the position that a collaborative virtual environment is a 3D immersive space in which 3D models are linked to databases, which carry characteristics. This premise has also been followed through other lines of thought, especially in construction planning and management by relating 3D models to time parameters in order to design 4D models (Fischer and Kunz, 2004), which are controlled through an interactive and multi-access database. In similar studies, 4D VR models have been used to improve many aspects and phases of construction projects by: 1) developing and implementing applications for providing better communication among partners (Leinonen et al., 2003), 2) supporting design creativity (Rahimian and Ibrahim, 2011), 3) introducing the construction plan to stakeholders (Khanzade et al., 2007), and, 4) following the construction progress (Fischer, 2000).

2.2 Virtual Reality as a Training Tool

VR applications are now increasingly being used as a part of the teaching and learning process. According to Zudilova-Seinstra et al (2009), VR as a teaching tool can contribute to the trainees' professional future by developing some learning activities beyond what is available in the conventional training systems. With respect to educational issues in the AEC industry, Sampaio et al. (2010) argued that the interaction with 3D geometric models can lead to active learner thoughts which seldom appear in conventional pedagogical conditions. Moreover, Juárez-Ramírez et al. (2009) asserted that when augmented to 3D modelling, VR could lead to better communication in the process of AEC training. However, VR training environments have arguably not yet fully reached the potential of reducing training time, providing a greater transfer of expert knowledge; or supporting decision making. This was primarily down to the ways in which this technology was augmented. It is therefore argued that educational training tools need to 'engage' learners by putting them in the role of decision makers and 'pushing' them through challenges; hence, enabling different ways of learning and thinking through frequent interaction and feedback, and connections to the real world context (Goulding et al., 2007). Furthermore, it is postulated that paring instructional content with game features, could engage users more fully, hence, help to achieve the desired instructional goals. In this respect, this study applied an input-process-output model (Garris et al., 2002) of instructional games and learning to design an instructional program which incorporated certain features or characteristics from gaming technology; which trigger a cycle that includes user judgment or reactions, such as enjoyment or interest, user behaviour such as greater persistence or time on task, and full learner feedback (Fig. 1).

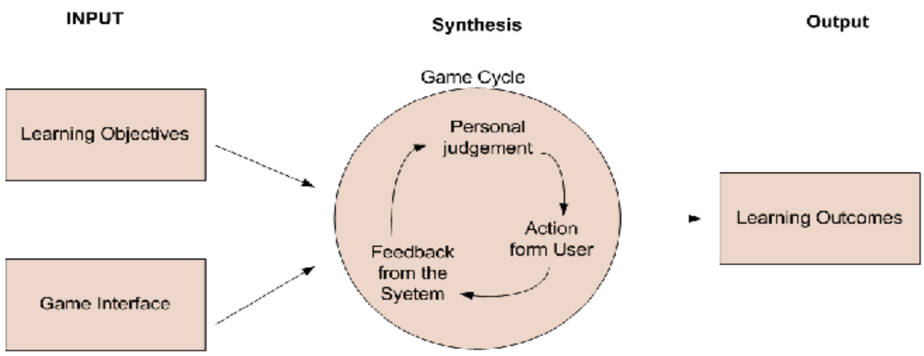


Fig. 1: Educational Game Model Input-Synthesis-Outcome (Garris et al., 2002)

3. Approach

The aim of the developed GVRSS in this study was to embrace 'real life' issues facing OSP construction projects in order to appeal to professionals by engaging and challenging them to find 'real life' solutions to problems often encountered on site. Hence, a real construction project was used to govern the authenticity of the learning environment. In this context, the prototype learning simulator was expected to allow 'things to go wrong', and hence, allow 'learning through experimentation' or 'learning by doing'. In this respect, although the 'scenes' within the simulator take place on a construction site, the target audience was focussed primarily on construction professionals e.g. project managers, construction managers, architects, designers, commercials, suppliers, manufacturers etc. Thus, the construction site was used as the main domain through which all the unforeseen issues and problems (caused through upstream decisions, faulty work etc) could be enacted, so that real implications could be better appreciated in respect of time, cost, resources etc. The real objective of the simulator was not to solve OSP problems *per se*, but rather allow things to 'go wrong' and demonstrate the implications of decisions taken. Furthermore, learning was planned be reinforced through a debriefing session, where learners are able to demonstrate additional understanding, particularly with respect to mitigating such issues in future OSP construction projects. In this context, learning occurs through the following:

- Learner autonomy - to make all decisions;
- Interactivity - environment provides feedback on the decisions taken, and their implications on the overall project (cost, time, resources, health and safety, etc);
- Reflection - users are able to defend decisions on the feedback provided, and have the ability to identify means to avoid/mitigate potential problems in the future such as: 1) OSP strategies e.g. Design for Manufacture Logistics and Assembly (DFMLA), 2) Business processes, procurement/contractual arrangements, project management, quality assurance etc, 3) Health and Safety procedures, 4) Supply chain integration, 5) New manufacturing technologies, open system, etc.

In essence, the main concept of the simulator was based on its ability to run scenarios through a VR environment to address predefined training objectives. In this respect, learning was designed to be driven by problems encountered in this environment, supported by a report critique on learners' choices, rationale, and defence thereof. As such, training aim and objectives of GVRSS prototype was designed to satisfy the following criteria:

- All scenarios and scenes should take place on a virtual construction site;
- Learners would predominantly play the role of a construction manager;
- Messages and training objectives would target the different stakeholders involved in a construction project, e.g. project managers, designers, architects, consultants, suppliers, manufacturers, etc;
- OSP working practices would be incorporated; and
- A user-friendly and highly interactive interface would be developed.

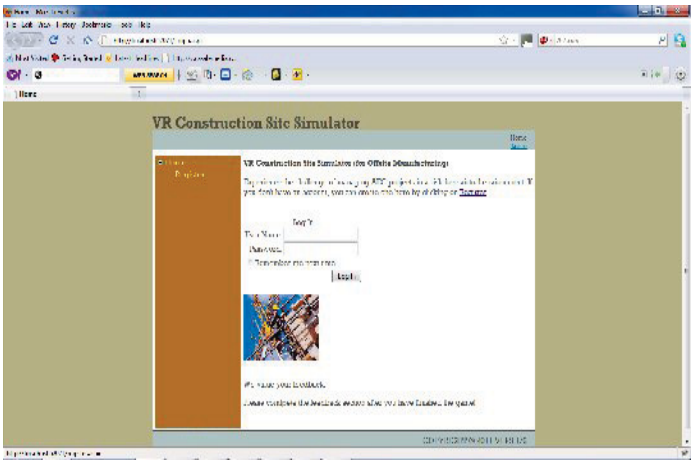
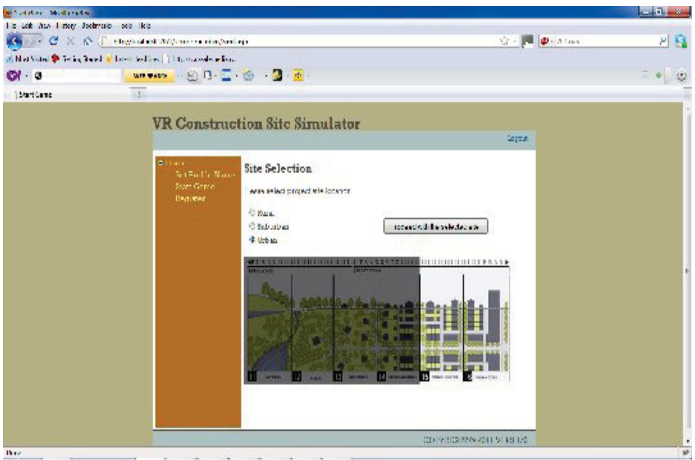
In accordance to these objectives, the Game-Like Virtual Reality Construction Site Simulator was designed and developed as an educational web-based simulation tool comprising of both non-immersive and immersive pages for providing novice construction managers with the opportunity of experiencing challenges of real-life AEC projects through simulated scenarios. In order to minimise interruption on the learners' reasoning process, the Graphical User Interface (GUI) was designed to be as simple and straightforward as possible with respect to data input. Thereby, the interface was designed as to be accessible through any standard web browser to provide users with login account details and other criteria, e.g. selection of available construction sites, projects, contractors, equipment, scenarios etc. All choices made by players as well as their registration data are then automatically recorded in MySQL database, which is also accessible through the immersive application for project simulation. After completing the initial decision-making process through the interactive ASP.Net Web Forms, learners are able to commence the training session, starting with a 'walkthrough' to experience and appreciate the complexity of the project. At this stage, the application provides users with a summary of the project and contract, and runs the simulation of the project within an immersive and interactive environment developed in Quest3D™ VR programming Application Programming Interface (API).

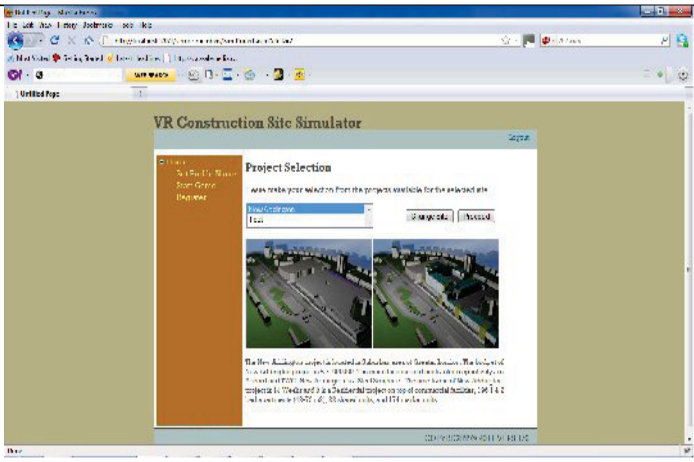
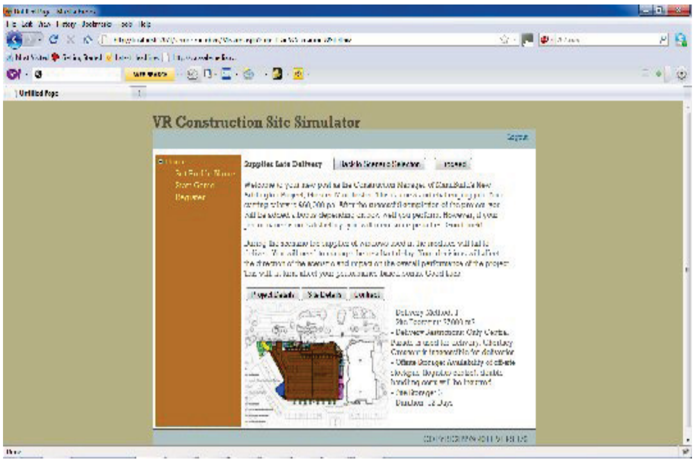
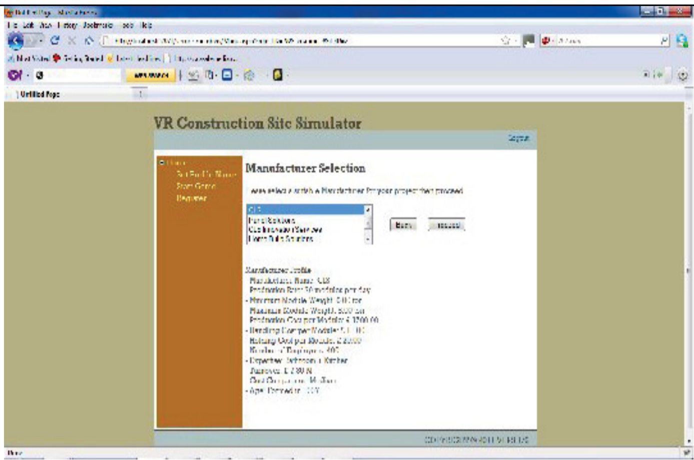
Within the simulated Quest3D environment, the users are able to experience the outcomes of all decisions made. They are also challenged by unexpected events designed according to the selected scenario, and are required to make decisions for dealing with these issues. The simulation runs in a fully immersive 3D environment, and users are able to navigate the whole interior and exterior spaces of the project site. At various points in the scenario, they are also able to interact with the different elements of the simulator in order to retrieve further information e.g. technical specifications, videos on selected OSP construction systems/details, project data etc. In order to keep the users in track of the project, the simulator also provides them with monitoring tools revealing the project time, latest assembled module, accumulative costs of the project, team communication etc. The monitoring and communication tools are embedded in different parts of the main interface as well as the facilitated standard embedded virtual PDA interface, which appears when required. The simulator ultimately records and tracks the users in the database and navigates to the conclusion page to reveal all scores of the user together with the logic behind the marking procedure.

4. Human Computer Interaction in the Developed Prototype

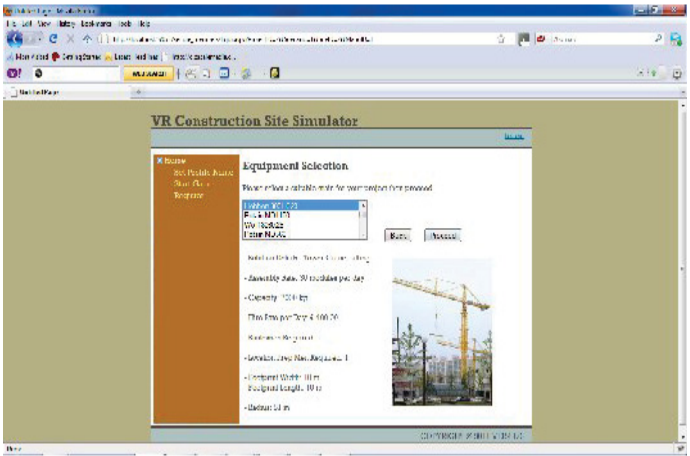
This section discusses the applied use case and discusses the various functions provided through the simulator to allow the user to interact with and hence learn about the different OSP aspects. Table1 outlines the first initial selection screens which allow the user to 'set the scene' through ASP.Net Web Forms. In this context, the user is able define the location of the project, the construction systems e.g. volumetric, panellised, or hybrid. Furthermore, the user is able to select the different relevant equipment. After the initial selection process, the user launches the simulation session. Different scenarios are triggered to exert 'pressure' on learners to think about options and consequences (as these affect the overall project cost, time, resources etc).

Table 1: VR Environment Initial Selection Screens

1		**User Login:** Users are required to read the instructions and enter their login information of create a new user account. Learning objectives It keeps record of accomplishment of the user and saves their performance to let them review their previous activities and learn from their decisions.
2		**Location Selection:** Users are required to select the location of the project e.g. rural, suburban, or urban. Learning objectives The location of a project has implications on access, equipment, storage etc - thereby affecting the triggered scenarios.

3		**OSP System Selection:** Users are requested to select the type of system/structure to explore, from a repository of stored systems. <u>Learning objectives</u> Different systems have different requirements – some suitable for some locations and not for others.
		**Scenario Selection:** Users are requested to select the type of scenario for the current 'Game'. In the next step, the users are provided with brief descriptions of each scenarios, details of the selected site, details of the selected OSP system, and also draft contract. <u>Learning objectives</u> Different scenarios have different learning outcomes based on the events embedded in them; so learners can experience different types of constructional project issues within each scenario.
4		**Manufacturer Selection:** Users are required to select the manufacture as the provider of building blocks. <u>Learning objectives</u> There are various issues associated with manufacturer selection. Through the assessment unit, the learner experiences the influences of different manufacturers on total costs of materials, completion duration, labour costs, fluctuating assembly costs, transportation costs etc.

5

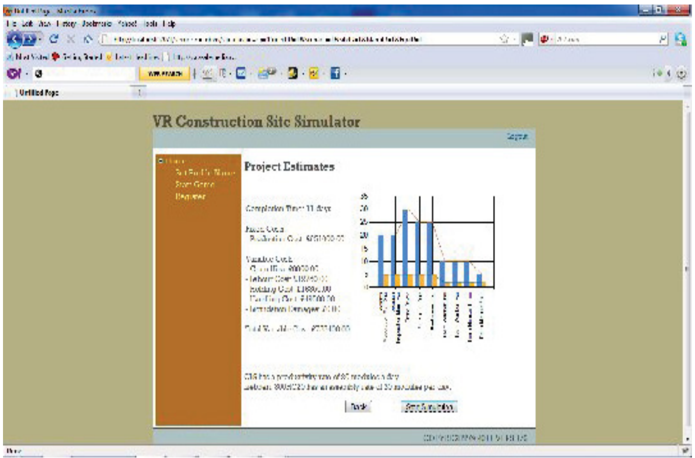


Site Set up and Equipment Selection:

Users are required to select the site set-up arrangements with respect to the equipment required.

Learning objectives

Logistics solutions are affected by the type of equipment and site set-up (in addition to equipment requirements and constraints).

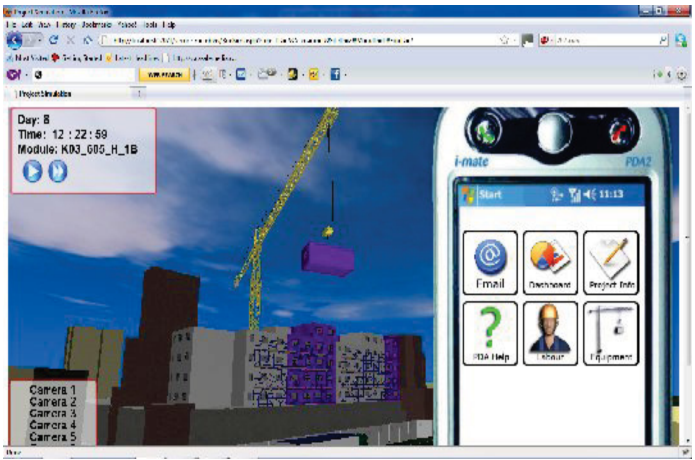


Summary of Decisions and Project Estimates:

Users are provided with a summary of all decisions up to the stage and some figures about the anticipated project costs, duration etc.

Learning objectives

Learner can compare the effects of all selected type of project site, OSP type, manufacturer and equipment selection, and scenario with those for the previous attempts.



Launch the VR Simulation Session

After these initial selections, users are able to run the VR simulation to experience how the project progresses based on their initial selections.

Different scenarios are triggered to exert 'pressure' on learners to think about options and consequences (as these affect the overall project cost, time, resources etc).

Fig. 2 illustrates a selection of the various functions available to the user of the simulator to fully interact with and retrieve information from the simulator during the VR simulation session. Further inclusion of the whole tree is considered for the exploitation phase. For a further description of the system architecture and storyboard for the developed prototype please refer to (Pour Rahimian and Goulding, 2011).

Fig. 2: The VR Simulation Sessions

5. Conclusion

A Game-Like VR Construction Site Simulator was developed in order to provide trainees with a virtual reality simulation of the construction site of the future. The developed simulator offers a risk free environment where learners (professionals) can evaluate how decisions they make would affect their business. This includes but is not limited to analysing issues occurred on the construction site such as: design concerns, process concerns, logistics concerns, and supply chain issues etc.

This paper presented capabilities of the developed Game-Like VR Construction Site Simulator (GVRSS) through three core phases: 1) Need Analysis and exploring existing, 2) System Development using Unified Software Development Process, and 3) examination of the impacts of utilising GVRSS on AEC actors employing the Charrette Test Methodology. It was argued in this paper that the enhanced engagement with the immersive project environment could lead to better understanding of the real-life AEC problems through experiencing them within a cyber-safe environment, hence leveraging the learners' cognitive processes. This study supports a novel approach of applying Game Theory to non-collocated design teams using Game-Like VR environments blended to Social Sciences Theory (social rules) and Behavioural Science Theory (decision science/communication science). This study contributes by identifying the causal drivers and influences associated with successful decision-making design in non-collocated design teams at the conceptual design stage. The findings of this study could be a stepping-stone in developing new insight and understanding in collaborative environments, particularly though new social interactions (and decision-making criteria) generated through Game Theory techniques. Moreover, this is the first of its kind to 'measure' and gauge actor involvement and positioning (cognisant of learner domain expertise). Furthermore, it uncovered new insight into organisational behaviour (within an AEC setting), along with social constructs; which could contribute to the wider understanding of Management Theory (organisational setting).

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STRATEGIES AND OPPORTUNITIES FOR EXPLOITING GAME THEORY APPROACHES IN VIRTUAL AEC TELE-COLLABORATION

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ABSTRACT: *The Architecture, Engineering, and Construction (AEC) sector is one of the largest industrial employers within the European Union (EU). However, whilst pockets of excellence exist, high levels of fragmentation have led to well-documented problems relating ostensibly to failures in communication and information processing. To mitigate this, various reports have highlighted the need to engage cutting-edge technologies related to process and organisational management, along with decision-making tools in order to leverage success. Recent innovations in Virtual Reality (VR) technologies and AEC decision- support toolkits have now excelled, enabling tele-presence engagement through collaborative environments. This research developed a Game-Like VR Construction Site Simulator (GVRSS) through three core phases: 1) Needs Analysis – to explore existing systems and needs through a series of focus groups and structured interviews with 17 AEC experts, 2) System Development - employing Unified Software Development Process, 3) Examination of the impacts of utilising GVRSS on AEC actors employing the Charrette-Test-Methodology. This paper explains the adapted Unified-Software-Development-Process, which employed iterative phases of Elaboration, Construction and Transition. Through the Elaboration stage, the requirements and priorities of the project were represented in an ontological structure, with generic arrangements identified for the knowledge objects, along with metadata wrappers. The next stage established object classes and their hierarchy to satisfy multiple abstractions. The final stage developed the user interface to comply with Human-Computer Interaction (HCI) protocols, and accessibility guidelines. The adapted Unified Software Development-Process ultimately took the GVRSS through an iterative testing procedure to diagnose and troubleshoot the prototype. This study presents a novel critique into the causal drivers and influences associated with successful decision-making design in non-collocated design teams at the construction stages. The findings of this study are a stepping-stone for developing new insight and understanding in collaborative environments, particularly though new social interactions (and decision-making criteria) generated through Game Theory techniques.*

KEYWORDS: *Virtual Reality, Construction Management, Game Theory, Collaborative Interfaces, Data Communication.*

1. Introduction

The European Union (EU) Architecture, Engineering, and Construction (AEC) sector is one of the largest industrial employers, encompassing more than 2 million enterprises and approximately 12 million employees. This represents 9.8% of the EU's Gross Domestic Product as it employs over 7.1% of the workforce (NGRF, 2010). The fragmentation of the AEC industry is well recognised, the consequences of which have led to well-documented problems relating ostensibly to failures in communication and information processing (Latham, 1994, Egan, 1998). These failures have contributed to an increased proliferation of adversarial relationships between the different parties involved in a project (Forcade et al., 2007), and adverse information loss (Fruchter, 1998, Cera et al., 2002) within the project lifecycle. It is therefore crucial for the AEC industry to employ cutting-edge technologies related to organisational management and decision making to leverage success; as the use of high-technology Information and Communications Technology (ICT) tools have been recognised as being particularly effective (Friedman, 2005).

The AEC sector and its engagement with ICT has revolutionised production and design (Cera et al., 2002), and has led to dramatic changes in terms of labour and skills needed (Fruchter, 1998). This is further reinforced by Goulding et al. (2007), concerning an increased tendency of using ICT tools within design and construction, especially for experimenting and experiencing decisions in a 'cyber-safe' in order to mitigate or reduce risks prior to construction. This idea is aligned with Petric et al (2002) regarding capability of such applications in predicting the cost and performance of optimal design proposals to search for 'good' solutions, and the implementation of such applications; as they enable design engineers to compare the quality of any one tentative solution against the quality of previous solutions. Consequently, the success of AEC projects is highly dependent upon the type, level and quality of the innovative communication exchange between various disciplines involved in the design and implementation phases.

Recent innovation in Virtual Reality (VR) technologies and AEC decision-support toolkits have now matured, enabling tele-presence engagement to occur through collaborative environments. Several opportunities are now available, including significantly improved immersive interactivity with haptic support that can enhance users' engagement and interaction. This research extends the findings of previous studies in this area, with specific emphasis on supporting the decision-making process at offsite construction stage. In essence, the aim of this study was to provide a flexible, interactive, safe learning environment for practicing new working conditions with respect to offsite production (OSP) in general, and Open Building Manufacturing (OBM) in particular; without the do-or-die consequences often faced on real construction projects. Hence, a VR interactive learning environment was sought which builds upon the multi-disciplinary practice-based training concept (Alshawi et al., 2007). In this context, the prototype aimed to enable disparate stakeholders, with different professional specialisations, to be exposed to the various aspects of OSP concepts. This approach was adopted in order to help overcome the problem of 'compartmentation' of knowledge (Mole, 2003). Furthermore, the prototype had to be flexible enough to allow any-time-any-place learning, so as not to be constrained to a particular place or time for learning to take place. As such, this research developed a Game-Like VR Construction Site Simulator (GVRSS) which comprised of three core phases: 1) Needs Analysis and exploring existing systems through a series of focus groups and structured interviews with 17 AEC experts, 2) System Development using Unified Software Development Process (Jacobson et al., 1999), 3) Examination of the impacts of utilising GVRSS on AEC actors employing the Charrette Test Methodology (Clayton et al., 1998). This paper explains the adapted Unified Software Development Process which employed iterative phases of Elaboration, Construction and Transition.

2. Approach

The main aim of the development of this GVRSS was to embrace 'real life' issues facing OSP construction projects in order to appeal to professionals by engaging and challenging them to find 'real life' solutions to problems often encountered on site. Hence, a real construction project was used to govern the authenticity of the learning environment. In this context, the prototype learning simulator would allow 'things to go wrong', and hence, allow 'learning through experimentation' or 'learning by doing'. In this respect, although the 'scenes' within the simulator take place on a construction site, the target audience is focussed primarily on construction professionals e.g. project managers, construction managers, architects, designers, commercials, suppliers, manufacturers etc. Thus, the construction site was used as the main domain through which all the unforeseen issues and problems (caused through upstream decisions, faulty work etc) could be enacted, so that real implications could be better appreciated in respect of time, cost, resources etc. The simulator was developed not to solve OSP problems per se, but rather allow things to 'go wrong' and demonstrate the implications of decisions taken. Furthermore, learning is reinforced through a debriefing session, where learners are able to demonstrate additional understanding, particularly with respect to mitigating such issues in future OSP construction projects. In this context, learning occurs through the following:

- Learner autonomy - to make all decisions;
- Interactivity - environment provides feedback on the decisions taken, and their implications on the overall project (cost, time, resources, health and safety, etc);
- Reflection - users are able to defend decisions on the feedback provided, and have the ability to identify means to avoid/mitigate potential problems in the future such as: 1) OSP strategies e.g. Design for Manufacture Logistics and Assembly (DFMLA), 2) Business processes, procurement/contractual arrangements, project management, quality assurance etc, 3) Health and Safety procedures, 4) Supply chain integration, 5) New manufacturing technologies, open system, etc.

2.1 VR Simulator Development Concept

The main concept of the simulator is based on its ability to run scenarios through a VR environment to address predefined training objectives. In this respect, learning is driven by problems encountered in this environment, supported by a report critique on learners' choices, rationale, and defence thereof. In this respect, the development encompassed two phases. Phase I embodies the development of the various scenarios, including the generation of reports etc; and Phase II, included the 'intelligence' components, including the interrogation of learners regarding their understanding, along with the assessment engine.

2.2 VR Simulator Development Framework

The simulator development framework encompasses four main activities: (identify training objectives; develop scenario(s); develop the VR environment; and validation of the prototype – see Fig. 1. This framework required extensive input from the construction industry in order to not only secure relevance, but also help govern authenticity of these stages.

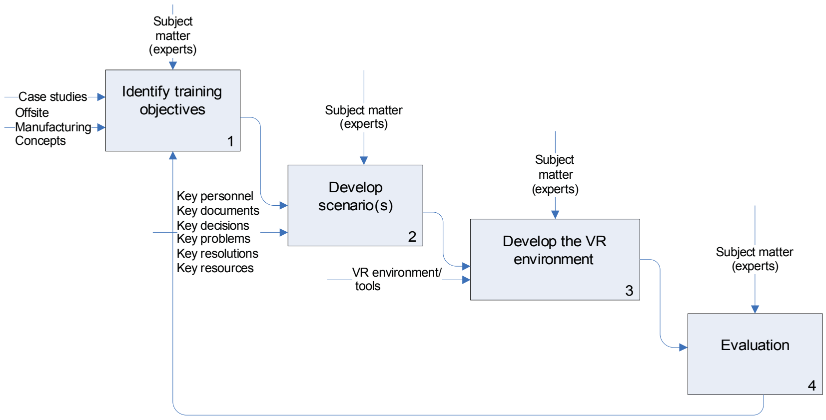


Fig. 1: VR Environment Development Framework

2.2.1 Training Objectives

The main training objectives underpinning the simulator were gathered from a synthesis of seminal literature covering the potential risks and threats facing OSP in general, and Open Building in particular. The capture of this knowledge was seen as fundamental for learners to fully appreciate, as it helps form the basis of appreciating how different stakeholders deal with the implications of such problems; and consequently, help learn how these could be mitigated for future practice. In this context, seven risks were identified: 1) To encompass late design changes, 2) To embrace issues such as the loss of factory production, or production capacity, 3) To include unpredictable planning decisions and designs that are not suited to OSM, 4) To capture the issues associated with tolerances, 5) To include the potential of suppliers' failure to deliver on time, 6) To allow for manufacturer bankruptcy, and 7) To deal with issues associated with alternative manufacturers.

2.2.2 Scenario Development

The scenarios were developed in order to expose learners to new working conditions and issues that they were likely to face on real construction projects employing OSP concepts. Therefore, it was deemed important to challenge learners to think about the routes of these problems, rather than just reacting to them. This concept was used to provoke learners to think 'proactively' about future OSP projects. In this context, the main scenario was based on identifying all possible problems/issues that are traditionally associated with OSP practice. These are colloquially referred to as problem 1, problem 2, etc – see Fig. 2. For each of these problems, there are a number of possible decisions with associated actions. Depending on the action chosen, the programme schedule, along with corresponding costs, time, and resources are affected.

These scenarios were used to simulate how OSP operates in real-life, in order to provoke learners to think 'how' and 'why' things may go wrong; and why consequently OSP may end-up being more expensive than the traditional way of working and thinking. As part of the learning process, learners are able to identify 'why' things went 'wrong', and 'how' these problems could have been avoided. Furthermore, a debriefing session is used to allow thorough interrogation of problems and choices selected, whereby learners are able to elaborate on the issues faced during the VR session; which helps to distinguish between 'being immersed' within the environment and the process of critical reflection that takes place outside the VR environment (De Freitas and Oliver, 2006).

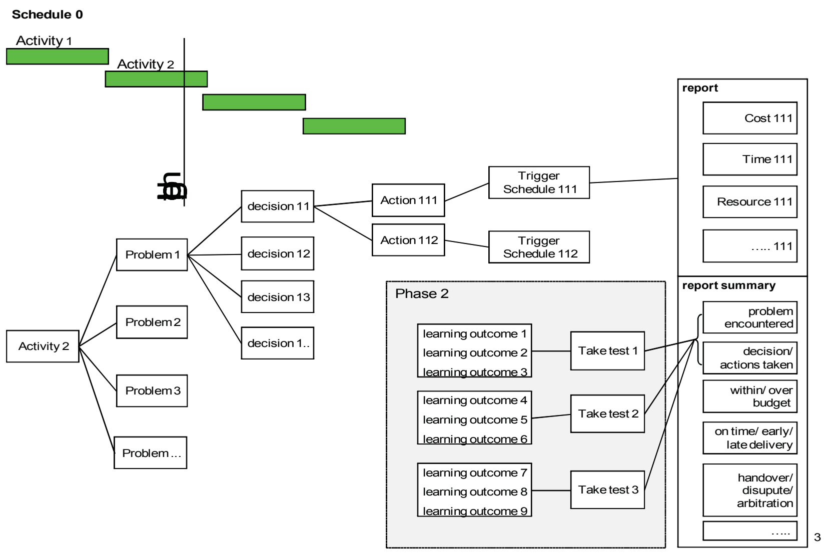


Fig. 2: Scenario Implementation Concept

To run a scenario, various information and data has to be input into the system in order to help populate the scenario. This data includes: a) Construction site type with respect to location and site scale, constraints, and layout b) Project type with respect to primary use of building (e.g. commercial or residential), budget allocated, type of structure, special layout and planning etc, c) Manufacturer type in terms of scope, capacity, location, costs associated and maintenance, d) Equipments hired in terms of size, capacity, assembly rate, required labour, hire rate etc, and e) work plan and associated possible interruptions/problems, including manufacturing option. This information is sourced from a predefined 'real' project and categorised in a relational database (see Section 3).

In essence, the simulator was expected to provide the learners with 1) simulation of site operations within real life and fast track time scales, 2) generation of reports based on all decisions made and their influences on project costs and risks, 3) saving and reloading sessions 4) running possible 'scenario directions/alterations' randomly based on the predefined interruptions and problems, 5) cross-examine learners' knowledge through transitions between different phases, 6) and generating feedback to learner on their performance. As such, the workflow of the simulator HCI was designed as presented in Fig. 3.

3. Prototype Development

In the first stage of the prototype development lifecycle, the project established the requirements and priorities (from Phase 1), represented in an ontological structure. The generic structure and content for the knowledge objects then were formulated with wrappers using metadata. The next stage established object classes and their hierarchy to satisfy multiple abstractions (and compliance with extranet metadata). The final stage developed the user interface to comply with Human-Computer Interaction (HCI) protocols, and accessibility guidelines etc in order to provide the system with a robust and reliable structure. The developed system includes simulated scheduling of the project, association of the 3D models and building blocks with project lifecycle, supply chain analysis monitoring for each building block or activity, management of delays in material delivery through sending emails to manufactory managers, and a final breakdown for project costs and labour.

3.1 System Architecture

Existing VR interfaces have ostensibly been formed based on one single idea: creating 3D models and incorporating them with some pieces of information so that both 3D models and information are editable through an interactive real-time interface (Pour Rahimian and Goulding, 2010). Contrarily, they differ from each other based on their architecture and the utilised methods for data creation and retrieval. However, data creation and retrieval methods in VR interfaces can be investigated from two different perspectives, namely creating 3D bodies of constructional elements per se and defining characteristics of the elements.

Although, creating 3D objects directly in VR environments is not impossible, this is usually created in CAD applications; since doing so in VR is often cumbersome and time consuming. Consequently, current VR interfaces can be categorised considering how they convert CAD models into VR elements. In terms of transforming design elements from CAD into VR, there are three de facto approaches used by different practitioners. Whyte et al. (2000), noted three approaches for this translation as being: 1) Straightforward translation approach and importing the whole environment from CAD to VR; 2) Library-based approach and putting the elements of construction in the library of VR environment then calling them when and where necessary; and 3) Database-oriented approach with a central database for controlling the module characteristics. Here, the database utilises both CAD and VR environments as graphical interfaces. Therefore, the third approach can be characterised as a combination of computer graphics and web programming. The database-oriented approach was selected for this project, as it was the only way that could facilitate learners to have access to the system from multiple remote locations.

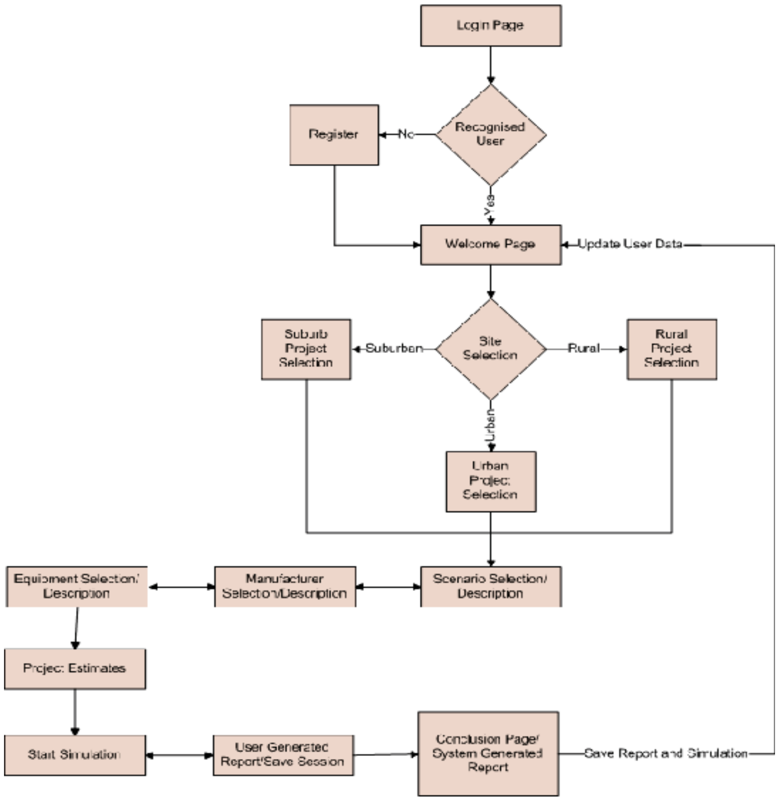


Fig. 3: Workflow of the simulator HCI

VR interfaces in the AEC industry vary also based on the method of manipulating the objects within the environment and the adapted programming method in VR interface. There are three major kinds of programming applications currently used by VR programmers as follows: 1) 3D Application Programming Interfaces (APIs); 2) Virtual Reality Modelling Language (VRML) and 3D web technologies; and 3) recent commercialised object oriented VR programming packages. In this respect, 3D Application Programming Interfaces (e.g., Open GL and Direct 3D) are principal environments for VR programming in C++ and Visual Basic. Falling in the category of computer graphics, they are capable to either create all models directly inside the space or/and import them from CAD applications. They are perfect environments for advanced programmers for creating Win32 console applications, which are used in developing computer games; however, integration of such interfaces with web programming is quite difficult and often leads to failures in cases of complicated works.

Virtual Reality Modelling Language (VRML) and 3D web technologies in their first version were made as a division of Open Inventor; thereafter, have become the international standard for 3D web modelling. These applications provide variety of facilities for manipulating immersive library based web interfaces; however, they lack the capability of integration with interrelated databases as they are not essentially database-oriented applications.

Recent commercialised object oriented VR programming packages contain built-in modelling environments for creating VR spaces directly or importing them from CAD applications. Such VR programming applications also contain logical libraries for defining behavioural links among the objects and simulating physical phenomena. Although the architecture of such applications is made based on APIs of C++, in some aspects they can offer a higher-level abstraction for programmers. Nowadays, there are three frontier commercial VR programming applications, namely Quest3D™, EON Reality™ and Virtools™. The outcomes of these applications are directly deployable into Visual C++ and Visual Basics web programming platforms (EON Reality, Inc., 2008). This makes them extremely flexible in terms of integrating VR programming (which is a part of computer graphics) with web programming and data mining. They also come with full Software Development Kits (SDKs) in order to help advanced programmers add some building-blocks and prototypes to create rationales or behaviours that were not originally provided by the application. Besides, the SDKs let programmers integrate their interfaces with particular VR I/O devices, e.g. Head-Mounted-Displays (HMDs) and data gloves. In this respect, this study proposed employing a database-driven approach using structured modelling phases and API based programming for the development stages. Linking 3D objects to datasets through a web environment for associating schedule of activities (4D visualisation), the system was able to optimise learning outcome through showing the changes in real-time.

Consequently, this study modelled all elements and components of construction site in either AutoCAD™ or 3D Studio Max™ as two of most the popular modelling software applications. The scenarios then were scheduled in MS Project™ environment. Moreover, all VR programming tasks were performed in Quest3D™ environment, whilst Active Server Pages (ASP.Net™) web development tool using C# ™ programming language was employed in developing the user interface. Finally, MySQL™ database which was compatible with both programming environments was installed on a server in order to track, manage, and transmit user data. The adapted Unified Software Development Process ultimately took the GVRSS through an iterative testing procedure to diagnose and troubleshoot the prototype regarding functionality, compliance, grouping, integration, maintenance, version control, and validation, which incorporated amending the interface to include any additional fields/delimiters identified in Phase 1. In essence, the architecture of the proposed simulator was designed as shown in Fig. 4.

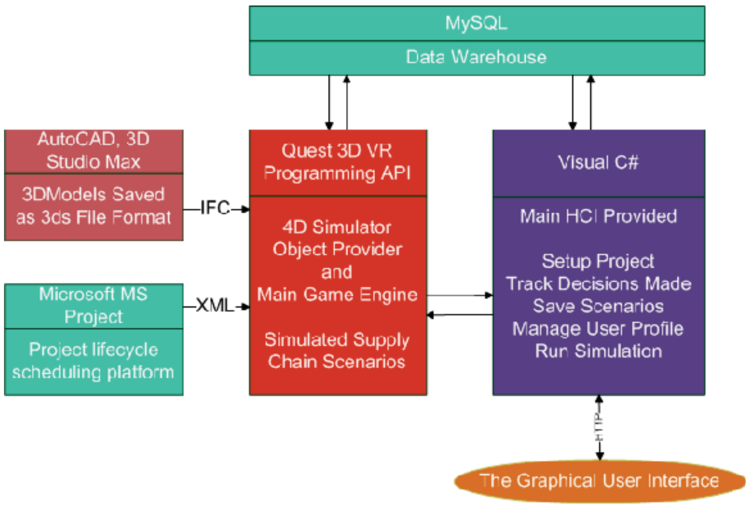


Fig 4. Simulator Architecture

3.2 3D modeling site elements in AutoCAD and 3D Studio Max environments

In this project system, AutoCAD and 3D Studio Max were is employed as the geometrical modeling platforms. Different construction site elements including both permanent (e.g. structural/architectural element and building blocks) and temporary (e.g. scaffolds and site barriers) constructional objects were created in detail. Model for constructional machinery and operational elements (e.g. Tower Cranes and Trucks) were also downloaded from CAD forums and websites. In order to optimise the final system performance, the project created the models at a very primitive level (e.g. beams, columns, walls, building blocks) and left the final assembly for Quest 3D as the 4D Simulation tool in which regeneration and repetition of single models in geometrical arrays do not demand allocation of huge space on the graphical memory. For the same reason, the project used a lot of bitmaps to give the illusion of secondary details, rather than actually creating them in 3D models. The bitmaps also helped the simulation look more realistic by visualising texture of different materials (e.g. concrete, wood etc). Ultimately, the models were converted into 3DS file format (in order to be readable by Quest 3D) and saved together in the same folders as their respective bitmaps.

3.3 Project Scheduling within the MS Project™ Environment

The study used MS Project software application for scheduling project lifecycle based on the developed scenarios. For each scenario, the temporal relationships amongst different assembly tasks were planned from the commencement of the project to the day of completion. In addition, it included random occurrence of some unexpected problems and interruptions during the project lifecycle. These schedules formed the essential basis for data regarding sequence amongst different assembly activities, duration of different constructional tasks and their commencement time and finishing time. Finally, the schedules were converted to MySQL databases which are accessible for both C# and Quest3D programming tools. Fig. 5 shows a sample project array within Quest3D that is imported from MySQL. The presented array in Fig. 5 identifies the details of assembly of various building blocks in terms of the 3D position of the building block, sequence of assembly, exact delivery time, and the machinery involved in transportation and assembly of it. Since all these data were stored in a relational database, the pieces of information regarding costs and labour for both building blocks and equipments were also automatically associated to all tasks. Moreover, this made it possible for learners to modify or update scheduling data through ASP.Net interfaces.

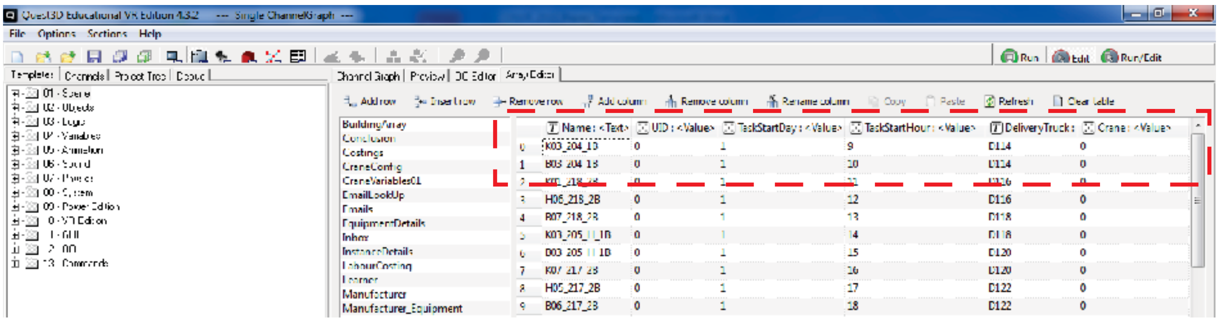
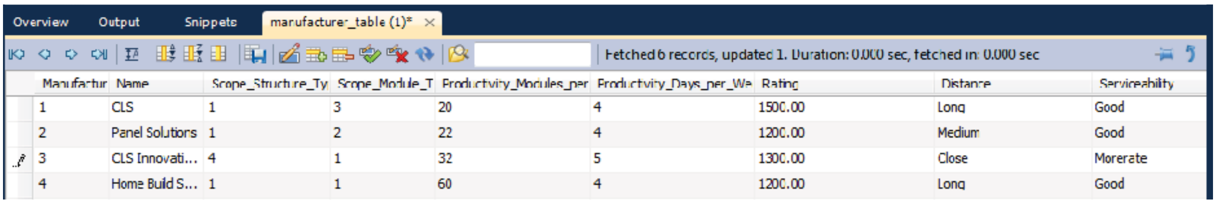


Fig. 5: Sample Project Array within Quest3D Imported from MySQL Database

3.4 Data Warehouse in MySQL™ environment

MySQL was selected as the platform to host the databases of this project as it is the only application that provides Quest3D with Software Development Kit (SDK). It is also accessible in MS Visual Studio environment through Devart DotConnect™ and ADO.Net™. Therefore, a relational database comprising of 44 different tables was created in MySQL to manage information regarding manufactures, equipments, labour and costs associated with different tasks, schedules for different scenarios etc. It provided the learners with full control on project data through both web forms and project simulation environment. Fig. 6 presents a sample table which provides the project with information regarding different manufacturers.



Fetched 6 records, updated 1. Duration: 0.000 sec, fetched in: 0.000 sec

Manufactur	Name	Scope_Structure_Ty	Scope_Module_T	Productvity_Modules_per	Productvity_Days_per_We	Rating	Distance	Serviceability
1	CLS	1	3	20	4	1500.00	Long	Good
2	Panel Solutions	1	2	22	4	1200.00	Medium	Good
3	CLS Innovati...	4	1	32	5	1300.00	Close	Morerate
4	Home Build S...	1	1	60	4	1200.00	Long	Good

Fig. 6: Manufacturers' Information Table within MySQL environment

3.5 Main Human Computer Interaction (HCI) interface with Visual C#

The designed ASP.Net interface using C# helps learners justify all project parameters and obtain the output as the simulated project site. The learners can also evaluate the details of potential assembly process throughout the planning procedure via the provided user interface. The designed simulator provides ASP.Net web forms as the initial GUIs that are used for transferring messages from users to the system in order to gather data regarding specifications of the desired construction process. Using these web forms, learners are able to control the type and sequence of construction tasks and make decisions on type and level of machinery involved in the project. The system also provides learners with estimates of project costs and time then proceeds to the simulation of the project. The simulation is generated in ASP.Net environment an embedded object by calling an external object exported by Quest3D. The embedded object is called by executing the following HTML code:

```
<body>
  <form id="form1" runat="server">
    <embed height="720" width="100%" checkupdate="1"
        type="application/quest" src="Quest3D_v59a.q3d"
        documenturl=" ~/ index.htm" id="Quest3DObject">
  </form>
</body>
```

Based on the collective decisions during the planning process and simulation time, the system calculates the total costs of the project and provides comparison between the results and average of similar projects. The system then generates a detailed report on the performance of learners. Fig. 7 presents C# code-behind and design interface of a sample project estimate associated with a chart generated through analysing data derived from project database.

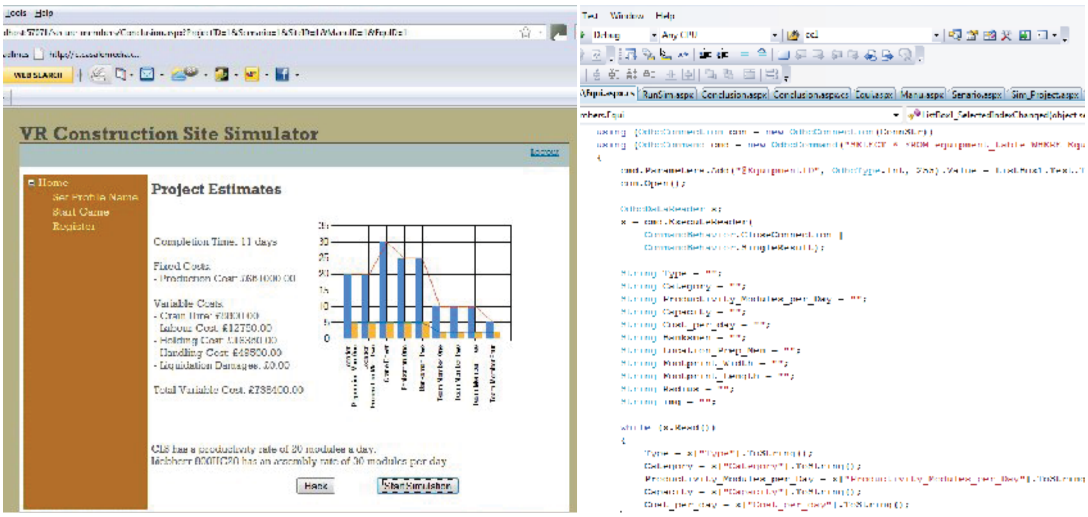


Fig. 7: Design Interface (Left) and C# code-behind (Right)

3.6 Quest3D VR programming environment

The geometrical 3D models of the constructional elements were imported by Quest3D in order to provide the basic entities and building blocks of VR programming. Quest3D is an Object Oriented (OO) programming platform in which the programming logic is formed through interconnection of Logical Building Blocks. In this project, the structure of the programme comprised of four main components: 1) The static 3D models of construction site including tower cranes, trucks, land, surroundings, and supporting elements which do not change from one learner to another (e.g. scaffolds); 2) Building Blocks as the dynamic 3D models of project; 3) Project Schedules for controlling all events of assembly and delivery process; and 4) Monitoring tools for keeping control of project time and resources.

As presented in Fig. 8, static elements were directly generated using 3DS and bitmap files, which appeared at particular locations. However, tower cranes and trucks were programmed to perform the desired animations at certain points of time. The modules of all static objects were directly connected to the project interface, except those for additional tower cranes and trucks that might or might not be hired by the learners. In these two cases, the modules were connected to the interface through an IF Toggle Channel in order to call the entities based on the preferences of user saved in the database. Another IF Toggle Channel was also connected to the main interface in order to facilitate switching the view into interior of Kitchens, Bathrooms, and Hallways.

In terms of assembling dynamic objects, the system relies on project schedule imported from MySQL database (as presented in Fig. 5), assembly sequence, and project time. Based on the given sequence, the system checks for assembly permission for each module and if the project time coincides with the time allocated to any module, programme runs the related animations in order to deliver and assemble that module. However, at some points some random interruptions occur in project sequence, so the implementation process continues only after the learner sends right emails to right personnel. In this case, a Trigger Channel reinitiates the performance of system subject to delivery of emails to the database. Delays in making the right decisions would result in an increased project cost and completion time.

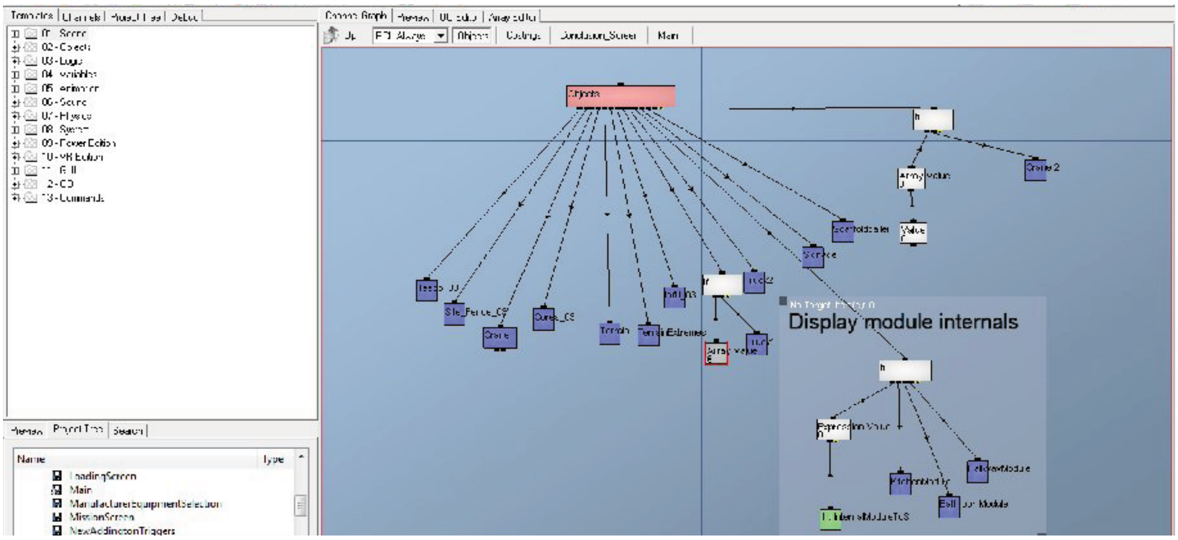


Fig. 8: Static Objects Connected to the Interface

Finally, with respect to project scheduling and monitoring tools, the system relies on system arrays formed and updated based on MySQL databases and particular algorithms which control project time and retrieve and visualise project cost in real-time. In essence, the simulator interface provides learners with a 4D simulated environment and an IPod interface for showing project statistics in real-time (see Fig. 9).

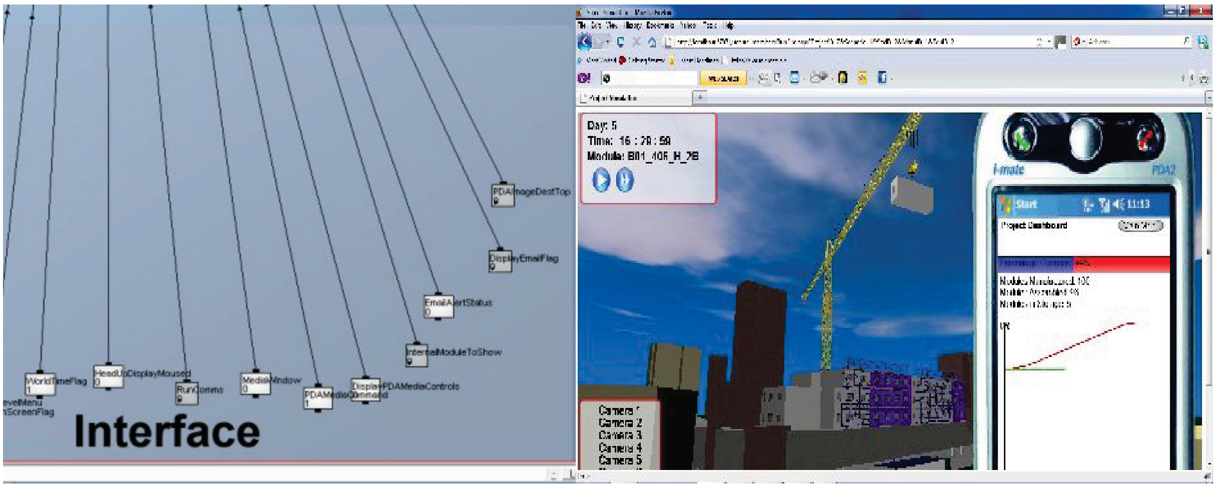


Fig. 9: Project Interface in Channel and Design Views

4. Conclusion

A Game-Like VR Construction Site Simulator was developed in order to provide trainees with a virtual reality simulation of the construction site of the future. The developed simulator offers a risk free environment where learners (professionals) can evaluate how decisions they make would affect their business. This includes but is not limited to analysing issues occurred on the construction site such as: design concerns, process concerns, logistics concerns, and supply chain issues etc.

This paper explained the adapted Unified Software Development Process, which employed iterative phases of Elaboration, Construction and Transition. In the first stage of the prototype development lifecycle, the project established the requirements and priorities of the project and represented them in an ontological structure. This study contributes to the body of knowledge in this area by identifying the causal drivers and influences associated with successful decision-making design in non-collocated design teams at the conceptual design stage. The findings from this study are a stepping-stone for developing new insight and understanding into collaborative environments, particularly though new social interactions (and decision-making criteria) generated through Game Theory techniques. This is the first of its kind to measure and gauge actor involvement, positioning, and organisational behaviour (within an AEC setting), along with social constructs – the nuances of which are likely to contribute to the wider understanding of Management Theory (organisational setting).

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VIRTUAL CONSTRUCTION: 4D PLANNING AND VALIDATION

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ABSTRACT: *Visual 4D modelling and planning technologies are becoming increasingly important in complex construction programmes facing the problems of advanced communication among stakeholders, better utilization of critical resources, and effective spatio-temporal coordination of works. Popular 4D tools and systems provide basic functionalities to simulate project schedules in virtual environments and to identify simple conflicting situations caused by collisions and interferences of construction elements and equipment units. Due to their complexity the collisions are usually detected in pseudo-dynamic mode assuming all the changes occurring in discrete time moments. Ultimately, it enables to anticipate and avoid potential problems at earlier phases and to reduce risks and waste at final construction phases often undergone to delays and reworks. The aim of this paper is to systemize possible spatio-temporal conflicts and to present advanced methods for more comprehensive and trustworthy validation of project schedules. For this purpose, an extended test suite is proposed by composing four complementary groups, namely: clash, join, workspace and path tests. Compared to usual clash testing, the introduced test suite helps to identify non-trivial defects like missing of supporting neighbouring elements, unavailability of required workspaces and absence of collision-free paths to deliver the elements to destination locations. For each group of tests the formal mathematical criteria and efficient computational strategies are presented and discussed. It's essential that they do not need detailed specifications of testing use cases and can be applied for large-scale construction projects simulated in pseudo-dynamic mode. Conducted computational experiments have proved the effectiveness and the feasibility of the proposed 4D planning and validation methods.*

KEYWORDS: *4D modelling, project planning and scheduling, validation, collision detection, path planning.*

1. Introduction

Visual 4D modelling and planning technologies are becoming increasingly important in complex construction programmes facing the problems of advanced communication among stakeholders, better utilization of critical resources and effective coordination of works taking into account both: spatial and temporal aspects. 4D tools provide a more comprehensive multidisciplinary analysis of the planned project activities by consolidating both 3D CAD models and scheduling information delivered from the project management systems like MS Project, Primavera Project Management, Asta Powerproject.

As a result, these tools have a tremendous potential to increase the communication efficiency and interpretation ability of the project team members (Dawood and Sikka, 2008). Improved communications are reached as a result of the simulation of project activities 'in progress' and the visualization of the construction programme as an animated scene reproduced with using graphic facilities or virtual reality environments. Another major benefit is that the 4D tools allow planners to trade off the temporal sequencing of tasks with their spatial distribution, resulting in a more robust and rehearsed project schedule (Tulke and Hanff, 2007). With the increasing pressure for shorter delivery schedules, a better utilisation of space resource on construction sites becomes more apparent. As opposed to the traditional Critical Path Method (CPM) widely employed by popular planning tools, the Critical Space Analysis (CSA) emphases the dynamic spatial distribution of the activity execution. This concept has been successfully adopted by the 4D modelling tools based on the industrial requirements capture (North and Winch, 2002).

Popular 4D modelling systems like Autodesk Navisworks, Bentley Schedule Simulator, Intergraph Schedule Review provide basic functionalities for simulating project activities in space dimensions and across time. Because of the complexity, projects are usually simulated in the pseudo-dynamic mode under common suggestion that most, if not all, objects appear, disappear or move strongly in the discrete time moments in which the project activities usually start or finish. Continuous behaviour for some animated objects is allowed, but the dynamic analysis of the whole scenes simulating large-scale industrial projects at detailed aggregation levels looks unrealistic. It is explained by intensive computations needed to carry out such analysis, as well as by enormous efforts to specify all the trajectories and kinematic rules, the construction elements and equipment units can move accordingly.

The available 4D modelling systems are also capable of identifying simple clashes caused by collisions and interferences of construction elements to be installed in the same place at the same time. Nevertheless, such analysis, being applied to the pseudo-dynamic mode, omits many other important issues leading to potential conflicts at project sites. Therefore, the construction projects are needed in more comprehensive and trustworthy methods of validating design accuracy and schedule adequacy. Ultimately, the methods would enable to anticipate and to avoid potential problems at earlier project phases and reducing risks and waste at the final construction phase often being undergone to delays and reworks.

The objective of this paper is to present the advanced validation methods that would identify both: usual clashes and more sophisticated spatio-temporal defects of project schedules. For this purpose, an extended test suite is proposed by composing four complementary groups, namely: clash, join, workspace and path tests. Compared to the usual clashes, the test suite enables to identify non-trivial conflicting situations, like missing of supporting neighbouring elements, unavailability of required workspaces and absence of collision-free paths to deliver the elements to destination locations. For each introduced group of tests the formal mathematical criteria and efficient computational strategies are presented and discussed. It's essential that they do not need detailed specifications of testing use cases and can be applied for large-scale construction projects simulated in the pseudo-dynamic mode. Being applied concordantly, the proposed 4D validation methods help to identify and to resolve suspicious issues of the prepared project schedules and to rise up the trustworthiness of whole construction programmes.

The rest of the paper is organized as follows: Section 2 describes the peculiarities of the visual scenes appearing in 4D modelling and planning applications and their underlying principles. In Section 3 we introduce four groups of tests to validate project design and schedules against the potential spatio-temporal defects. Special attention is paid to the mathematical criteria and efficient computational methods for performing such tests for the large-scale construction project data. Various examples and illustrations are presented to explain each of the introduced group of tests. The results of some computational experiments are discussed in Section 4 to prove the feasibility and the effectiveness of the proposed 4D planning and validation methods. Their benefits are shortly summarized in Conclusions.

2. 4D Modelling and Planning Applications

Recently free, the commercial applications for 4D modelling and planning are becoming more and more accessible. Although the applications may differ in some functions and performance characteristics, most of them focus on the same range of problems and share common principles (Seliga 2007).

One of the underlying principles is the consolidation of 3D models prepared using the CAD tools and scheduling information delivered from the project management systems. The consolidation assumes linking CAD elements and project activities, as well as defining dynamic behaviour patterns for the linked elements.

The presented screenshot of the Synchro system illustrates this principle (see the Figure 1). Being consolidated and managed through the graphic user interface, the 4D project data can then be visualised and explored against potential spatio-temporal conflicts. The graphical user interface of the Synchro combines and coordinates both: the Gantt chart, traditional for most project management applications, and the 3D views, typical of the CAD systems. By shifting the focus time line at the Gantt chart manually or by running the simulation in the automatic mode, the user can observe the project progress in multiple views from the most convenient perspectives. The view camera positions are preliminary chosen by the user, so that most interesting and critical issues of the project plan can be thoroughly investigated. The focus time line may remain fixed at the Gantt chart as camera position in one of the views is changed. It is usually done when the user tries to investigate the model snapshot by applying zooming, translating and rotating operations over the scene in the scope of well-known navigation paradigms like ‘walk’, ‘examine’, ‘bird’s eye’.

The second principle is to support complex visual scenes and appropriate simulation scenarios. We consider that the scenes originating from 4D modelling and planning applications have the following characteristics:

Large scale: the scenes may consist of thousands and millions of objects with their own 3D model representations and dynamic behaviours. The objects can be both: relatively simple shapes and assemblies with sub-assemblies, as a result of which the complexity of individual objects and scenes can be essentially varied.

Mixed geometry: the objects may be canonical geometry primitives, algebraic implicit and parametric surfaces, like quadrics, NURBS and Bezier patches, convex and non-convex polyhedrons, solid bodies given by constructive solid geometry (CSG) or boundary representation (BREP).

Pseudo-dynamics: All the scene events are discrete in time and known in advance (in contrast to the real-time simulation in the virtual reality environments). They may be appearance or disappearance of the scene objects, as well as their discrete movements. The dynamic simulation of the whole scenes looks redundant and unrealistic for real construction projects. Nevertheless, it is admitted that some part of the objects can move smoothly along the specified trajectories in accordance with the prescribed kinematic rules.

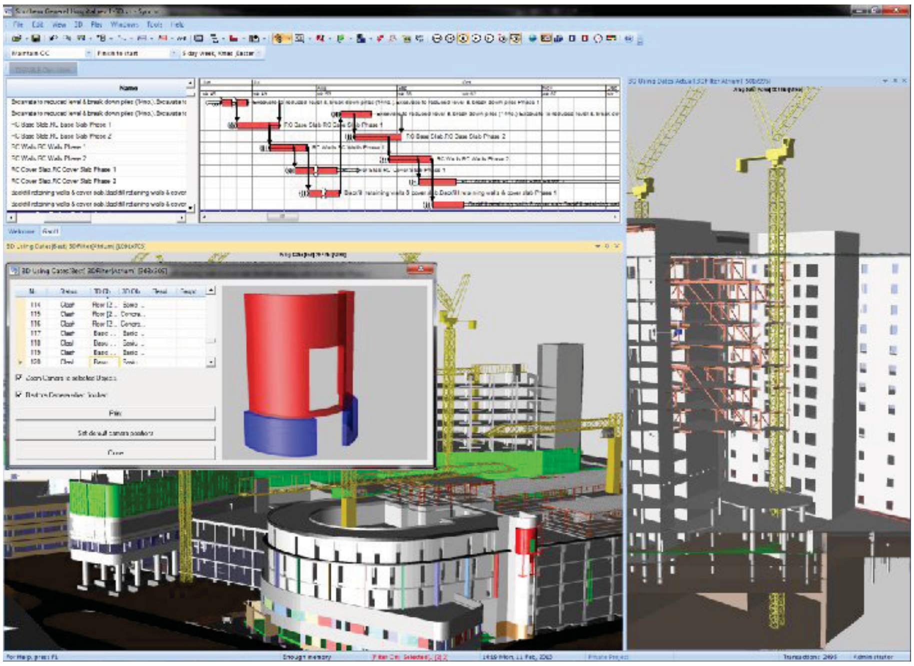

Fig. 1: The Synchro graphic user interface for visual representation of the 4D project data and spatial coordination.

The third important principle conveys the trustworthiness of the obtained validation results in conformity with the original project design and plan schedule. As an example, consider how the validation can be accomplished using the Synchro. Calling the spatial coordination tool the user runs a clash analysis and gets a detailed report about all the detected issues. The analysis can be applied to both: static scenes recovered at fixed time points and dynamic scenes reproducing project activities throughout the whole duration. Special parameters, like clash tolerance and penetration depth can be defined explicitly by the user to adjust clash criteria and to extract only meaningful conflicting situations. The obtained results are visually represented as an interactive report, by means of which the detected clashes can be easy localised in the Gantt chart and 3D views (see the Figure 1). An important circumstance is that the Synchro provides both 4D modelling and planning functionalities. Due to this advantage over other similar systems, the user can resolve most clashes directly in the application. It is usually done by correcting the project schedule (or even the whole project plan), as well as by changing the construction site layout.

Nevertheless, the trustworthiness of the 4D modelling and validation is a critically important problem because simple clashes could not be taken as comprehensive correctness criteria for the project design and schedules. Consider how the discussed validation procedure can be significantly improved using the extended test suite.

3. Validation Tests

The proposed test suite is composed of four main groups that can be checked using the so-called clash, join, workspace, and path tests. Clash tests enable to identify simple defects by checking for contact between a pair of scene objects. Join tests complement these checks by exploiting the following evident principle: the construction elements cannot be correctly installed when isolated from the supporting or neighbouring elements. Workspace tests focus on the feasibility of scheduled activities which can be successfully carried out only if other concurrent activities are not running in the same space. Path tests are intended to guarantee the possibilities to deliver each construction element to the assigned destination position along a collision-free path avoiding any obstacles and satisfying the imposed kinematic constraints.

Clash, join and workspace tests can be performed using well-known mathematical methods of collision detection. Although these methods belong to the traditional chapters of the computational geometry and are incorporated in the most popular CAD and computer graphics systems, the performance remains a crucial factor for analysis of complex dynamic scenes, particularly, the scenes originating from 4D modelling and planning applications. Path tests can be accomplished using the theory of motion planning and its numerous applications. Unfortunately, both: collision detection and motion planning methods have relatively high complexity that grows extremely with the input data volume. Therefore, efficient computational strategies must be developed and applied to perform the proposed tests on large-scale construction project data. Let's discuss each of the introduced group of tests in more details.

3.1 Clash tests

Collision and interference checks constitute the first group. The problem of collision detection or contact determination between two or more objects is fundamental for computer animation, physical based modelling, CAD/CAM applications, robotics and automation, computer graphics, and virtual reality as well. The survey of the traditional methods and available tools can be found in (Lin and Gottschalk, 1998).

It is said that two objects o' and o'' don't collide with each other if the distance between them is larger than the given nonnegative threshold: $dst(o',o'') > \varepsilon_0 \geq 0$. Here the function is defined as a minimum Euclidian distance among all the pairs of points $x' \in o'$ and $x'' \in o''$ belonging to the corresponding objects: $dst(o',o'') \equiv \min_{x' \in o', x'' \in o''} \|x', x''\|$. The threshold ε_0 plays the role of the absolute computational tolerance with which the collisions are determined. Figure 2 presents an example of the clash testing with a given threshold parameter. It identifies the issue for circle O_1 and rectangle O_2, but proves the avoidance of collisions between circle O_1 and rectangle O_3.

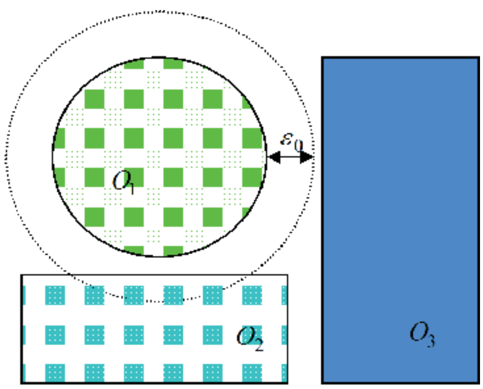

Fig. 2a: An example of clash testing.

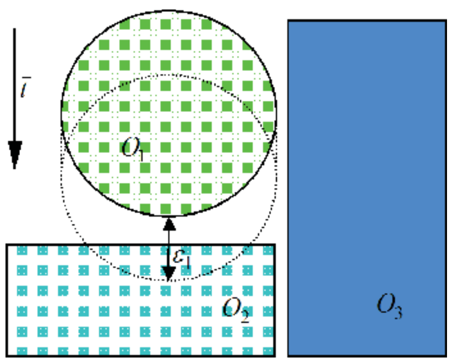

Fig. 2b: An example of join testing.

Four fundamental approaches to the collision detection problem have been proposed and successfully implemented to deal with different statements and application peculiarities. These are exact interference detection, spatial decomposition, bounding volumes techniques and methods exploiting temporal coherence

(Jimenez et al., 2001). They all focus on reducing the number of pairs of objects that need to be checked for contact, as well as on reducing the total computation cost of such checks.

Exact interference detection is typically applied to the canonical geometry primitives, CSG objects, convex polyhedrons, algebraic implicit and parametric surfaces like quadrics, NURBS and Bezier patches (Lin and Gottschalk, 1998). Octrees, k-d trees, BSP-trees, BRep-indices, tetrahedral meshes, and regular grids are all examples of the spatial decomposition that assumes preliminary subdivision of the space occupied by the scene objects. In different ways it exploits the same evident principle: one needs to check for contact between only those pairs of objects that are in the same or nearby cells of the space partition. Bounding volumes are quite a popular approach assuming the covering of objects by primitives and the effective localization of potential collisions due to the fast "rejection" tests for intersection of the bounding primitives. A lot of methods, such as sphere trees, cone trees, cylinder trees, strip trees, AABB trees, OBB trees, BOXTree, k-DOP trees, FDH have been developed and thoroughly investigated in the literature (Klosowski 1998; Zachmann, 1994). And finally, temporal coherence methods tend to exploit the latency of dynamic scenes. Sweep and prune techniques, collision queues with bounds on velocities and accelerations, S-bounds and four-dimensional intersection testing belong to this underlying direction (Cameron, 1990).

An efficient computational strategy for collision detection was proposed and investigated in our work (Semenov et al., 2010). The strategy exploits the peculiarities of the spatial and temporal coherence of the scenes appearing in the 4D modelling and planning applications. Combining spatial decomposition, bounding volumes and temporal analysis methods, the strategy yields substantially faster collision detection than the previously known methods applied separately or discordantly. The conducted computational experiments showed relatively high performance characteristics making possible to apply the strategy to large-scale construction scenes on typical computer configurations.

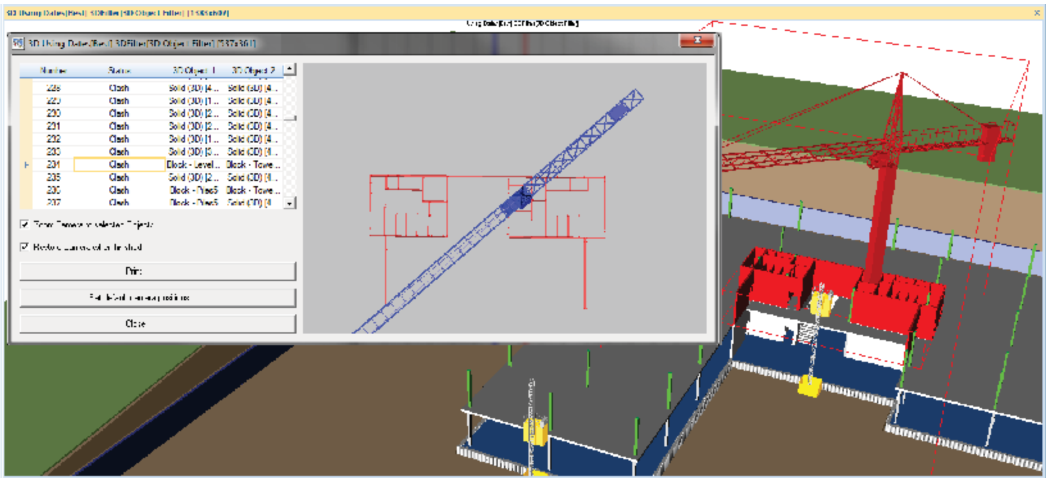

Fig. 3: The Synchro application screenshot illustrating clash identification.

Figure 3 presents a practical example of clash identification in the multi-story building project using the Synchro system. The detected clash in a project schedule is caused by started works on the next floor before removing the crane equipment.

3.2 Join tests

The second group of the validation tests is the so-called "join checks". They imply checking for contact between the new objects that appeared in the scene and the existing objects located in the same or nearby positions. Indeed, a newly installed construction element cannot "hang in the air" and must be supported by lower elements or fasten together neighbouring elements. If an object is removed from the scene, then the remained objects have to be suffered to join checks as they could be based on the removed object. To perform join tests, they must be preliminary specified in a form allowing mathematically strong validation. Let's discuss how such a specification can be compiled being based on the introduced adjacency and conjugacy relations among objects of a scene S.

General specification of joint tests should include the set of objects $S^* \subseteq S$ considered to be priori installed correctly. By pointing out such objects, we define initially deployed elements of the scene S, such as ground, stationary infrastructure, etc. The specification may also contain information about particular objects and additional requirements assuming the availability of neighbours for the installed objects in their final destination positions.

In most practical cases, a simple mathematical model can be utilised for this purpose. As suggested, an object $o' \in S$ is installed correctly and satisfies to corresponding join test if some object $o'' \in S$ has been already installed correctly at the distance not far from the given distance threshold: $dst(o',o'') \leq \varepsilon_1$. In some cases, the directions should be additionally prescribed to particular objects to constrain the admitted location domains of neighbouring objects. For example, by refining the direction as top-down, the join check can be reinterpreted as a gravity test taking obvious physically-sound meaning: the installed element must have supporting neighbours below and the removed element should not have neighbours above if they have been based only on this element. As opposed to clash test assuming the absence of neighbour elements, join test requires the existence of such elements in nearby positions along the specified directions. To be applied concordantly, tolerance parameters of clash and join tests must be chosen in a proper way: $\varepsilon_0 < \varepsilon_1$.

An object $o' \in S$ is adjacent to an object $o'' \in S$ (or $o' \to o''$) in the specified direction $\bar{t}$ at the distance ε_1 if and only if exists vector $\bar{t'}$ collinear to $\bar{t}$ so that its length is smaller than the given distance ($\|\bar{t'}\| \leq \varepsilon_1$) and the object o' being translated by the vector $\bar{t'}$ collides object o''. In practice to identify the adjacency between objects o' and o'', object o'' should be checked against the collision with object o''' obtained by extrusion of the object o' along vector $\varepsilon_1 \bar{t}/\|t\|$. Zero threshold parameter is assumed to be applied to this check. If the collision is identified, then object o' is adjacent to object o''. Figure 2b presents an example of join testing. Circle O_1 is identified to be adjacent to rectangle O_2 with the specified direction $\bar{t}$ and the given threshold ε_1, but not adjacent to rectangle O_3.

Sometimes we also apply an alternative definition of the adjacency being invariant with respect to any specified direction. An object $o' \in S$ is adjacent to an object $o'' \in S$ (or $o' \leftrightarrow o''$) at distance ε_1 if and only if a vector $\overline{t'}$ exists, so that $\|\overline{t'}\| \leq \varepsilon_1$ and object o'' being translated by vector $\overline{t'}$ collides object o''. As opposed to the directional adjacency, this relation is symmetric. An object $o' \in S$ is conjugative to object $o'' \in S$ (or $o' \Rightarrow o''$) if there is a sequence of objects $o_1, o_2, \dots, o_n$ so that $o' \rightarrow o_1, o_1 \rightarrow o_2, \dots, o_n \rightarrow o''$. Objects $o', o'' \in S$ are mutually conjugative (or $o' \Leftrightarrow o''$) if there is a sequence of objects $o_1, o_2, \dots, o_n$ so that $o' \leftrightarrow o_1, o_1 \leftrightarrow o_2, \dots, o_n \leftrightarrow o''$.

Thus, join tests can be formalised mathematically. Any object $o \in S^*$ is considered to be a priori installed correctly. Object $o' \in S \setminus S^*$ is being installed correctly if and only if exists the object $o'' \in S^*$ so that $o' \Rightarrow o''$. Object $o' \in S$ is being removed correctly if and only if for any object $o'' \in S$, $o'' \rightarrow o'$ exists the object $o''' \in S^*$ so that $o'' \Rightarrow o'''$. As all the defined relations are transitive, the conjugacy relation can be obtained by transitive closure of the corresponding adjacency relation for the set S. Using the definitions above and the obtained formula, an effective algorithm for both static and pseudo-dynamic scenes can be derived.

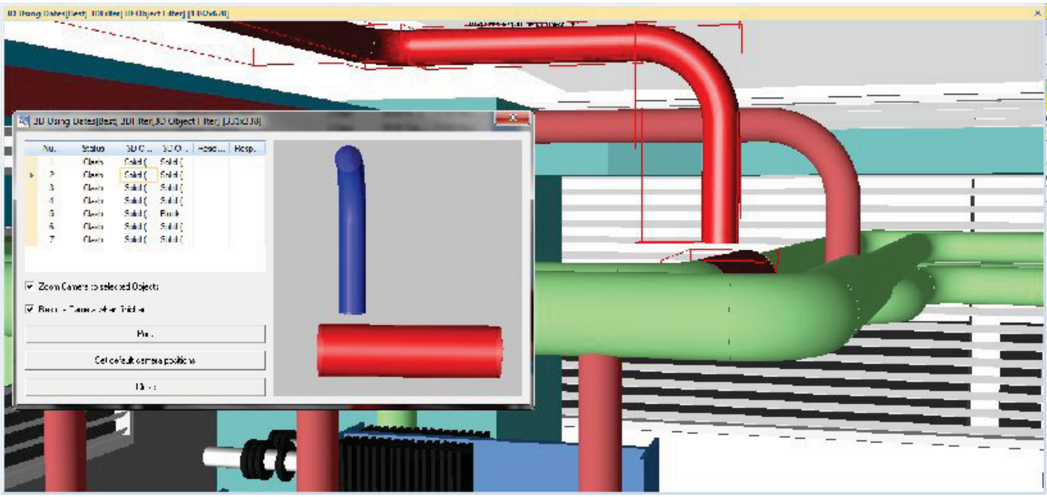

Fig. 4: The application screenshot illustrating join testing.

The presented Figure 4 illustrates another obvious problem in the project schedule resulting in "hanging" of the installed piping element without any supporting neighbours. Being included in test suite, joint checks help to identify and remove such spatio-temporal defects, thereby rising up the trustworthiness of both project design and plan schedules.

3.3 Workspace tests

To provide a safe and productive environment, project managers need to plan the work spaces required by construction activities. Work space planning allows different interpretations and covers meaningful statements like site layout planning, space scheduling, and space occupation balancing. The detailed descriptions of these approaches can be found in Akinci and Fischer (1998).

Since construction schedules may consist of hundreds and thousands of activities requiring multiple types of spaces, it is practically impossible to expect project managers to specify manually all the data necessary for representing workspaces in complex scenes. At the same time, semi-automatic techniques are able to generate spaces using construction templates including their relative orientation with respect to a reference construction element and requiring a certain size (Akinci, Fischer2, Kunz 2000).

In this section we consider two underlying methods of defining and performing workspace tests. The first method corresponds to the space scheduling statement mentioned above. It implies defining an exclusive workspace, $s_i = S$, $i = 1..n$ for each schedule activity a_i and corresponding construction element $o_i \in S$ installed, removed or moved during this activity. A correct schedule must avoid conflicting situations when workspace of one activity is crossed by elements or workspaces of other running activities, thereby satisfying the conditions $dst(s_i, o_j) > \varepsilon_0$ and $dst(s_i, s_j) > \varepsilon_0$ for any $o_i, o_j \in S$, $s_i, s_j \in S$, $i \neq j$. This would mean that concurrent activities must not share the same spatial resource during the common time interval. Each workspace may be represented as a simple box or a set of solids reproducing different concepts and requirements, like labour crew space, equipment space, hazard space. It is admitted that objects and spaces belonging to the same activity can be mutually intersected, but situations of intersections with other spaces must be excluded.

Figure 5 illustrates an example of workspace testing. Objects $O_1$and O_2 have been assigned to the activities A_1 and A_2 assuming availability of free spaces S_1 and S_2 necessary for their successful performing. Since activities A_1 and A_2 share the common time interval (t_0, t_1) and spaces assigned to these activities intersect in the region S_{12}, spatio-temporal collision is being identified.

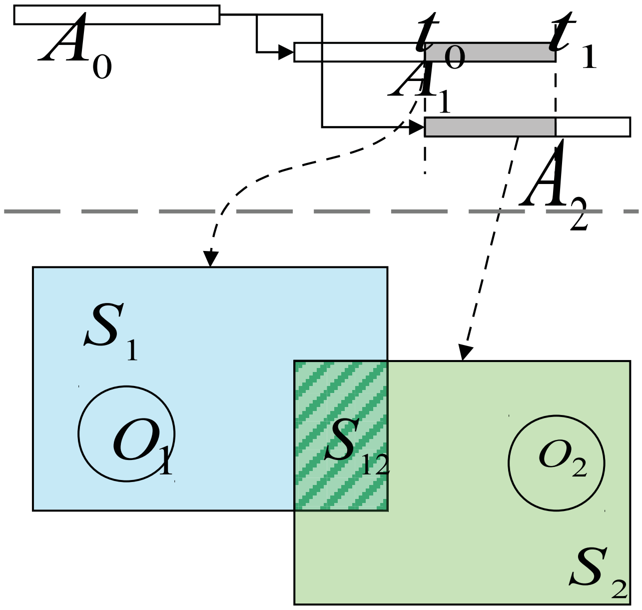

Fig. 5: Space testing example.

The second method relates more to the space occupation balancing. The line of balance is a conceptual plot widely used in project management systems to visualize resource utilization degrees across time. The proposed method assumes the workspaces to be non-exclusive spatial resources shared by different activities simultaneously. Certainly, the specification of all admitted combinations of human activities, construction methods and technologies which could be performed in the given workspace looks extremely difficult to project managers. Therefore, we propose to use the following mathematical model for space sharing. It is formally expressed by pseudo-Boolean functions of the form $f: B^n \to R$, where $B = \{0,1\}$ is a Boolean domain, R is a real domain and n – is a nonnegative integer called the arity of the function.

Let's introduce a Boolean indicator $a(t) \in B^n$ indicating which activities started, but not finished at the given time moment t so that for every activity a_i the indicator element $a_i(t) = 0$ if the activity is not running and $a_i(t) = 1$ in the opposite case. Then, a generic constraint for workspace utilization can be represented by a multi-linear polynomial function as follows:

$$f(a,t) = \sum b_i a_i(t) + \sum b_{ij} a_i(t) a_j(t) + \sum b_{ijk} a_i(t) a_j(t) a_k(t) + \cdots \leq 1$$

where all the polynomial coefficients $0 \leq b_i, b_{ij}, b_{ijk} \leq 1$ are normalized. It can be seen that the presented constraint enables to specify various meaningful cases of workspace utilization.

If a workspace is exclusive, then the coefficients can be defined as $b_i = 1$ for all the activities a_i, $i = 1..n$. The constraint is satisfied only if the activities are executed one after another and it is violated if some activities are running at the same time. If an activity a_i is allowed to run concurrently with other activities a_j, $i \neq j$, then corresponding coefficient must be set to zero value $b_i = 0$. If a workspace can be shared by all the activities simultaneously, then the constraint takes the confluent form with all the zero coefficients $b_i = 0$, $i = 1..n$. Certainly, the coefficients may not necessarily be integer. More complicated cases are covered by using real values. For example, if $b_i = 1/2$, $i = 1..n$, then any pair of activities is admitted to be run simultaneously; if $b_i = 1/3$ – any three activities, etc. Thus, the introduced coefficients define fractions of the common workspace utilized by each involved activity and can be adjusted individually.

The use of triangular matrix b_{ij} or even tensor b_{ijk} enables to specify more sophisticated cases of the workspace utilization assuming particular combinations of running activities. As an example, let set the coefficients of the matrix to unit values $b_{ij} = 1$ for all $i, j = 1..n$, $i < j$. Thus defined constraint allows any pair of activities to be run concurrently, but prevents combinations with more number of activities. If the activities a_i, a_j $(i < j)$ do not conflict with other activities being executed in parallel, the corresponding coefficient is set to zero value $b_{ij} = 0$. This would mean that any other pair of activities can be combined with the non-conflicting one. For brevity, we omit many other interesting cases. It is essential that in most practical cases the number of non-zero elements of the vector, matrix or tensor representation is not large that gives the project manager to directly input the needed values.

Being specified and interrelated with involved activities, the workspaces can be tested against imposed constraints. The computational methods needed to perform such tests are similar to those applied for clash tests with the exception that both construction elements and related workspaces are suffered to collision analysis. Certainly, pairs of elements and workspaces belonging to the same activities should be excluded from the consideration.

3.4 Path tests

The fourth proposed group of validation checks is path tests. These tests are intended to control the possibilities to deliver each construction element or equipment unit to its destination positions, or in other words, the existence of collision-free paths from some initial outdoor position to the final installation position. For removed elements the existence of paths from installation positions to the outdoor position is checked too. Path tests make sense only for those scene objects whose continuous behaviour has not been specified exactly. Clash and interference checks performed in pseudo-dynamic mode can guarantee absence of collisions only in discrete time moments rather than over whole time intervals when the objects are moving. Therefore, clash testing is not comprehensive and complementary path tests would add value to the evolved validation technology. For the animated objects moving along specified trajectories in accordance with the prescribed kinematic rules, usual clash testing enables to identify all the discussed critical issues.

So, if an object $o_i \in S$ appears in the scene S at a fixed time moment, we require the existence of a collision-free path $p(\tau)$, $\tau \in [0;1]$ from the predefined outdoor position $p(0) = x_0$ to a destination position $p(1) = x_1$ so that the object o_i, being placed in any intermediate position and represented as

$o_i' = p(\tau) \circ o_i$, does not collide with other scene objects $dst(p(\tau) \circ o_i, o_j) > \varepsilon_0$, for any $i \neq j$ and $\tau \in [0;1]$. Note that this definition admits the object o_i to be translated and rotated, but neglects the speed with which the object can move under accepted assumptions. Figure 6 presents an example of path testing for object O being moved from the position A to the destination position A'. Among possible routes like P_1 and P_2 , the collision-free path P_2 has been found. Evidently, route P_1 leads to the clash between the object and the environment.

The presented statement relates to the global path planning problem. Unlike local planning, it has relatively high computational complexity that extremely grows with the input data volume. Extensive research efforts have been directed towards these problems (LaValle 2006). Most reports have concluded that the algorithms work well in simple 2D environments, but require much larger computation resources in large-scale dynamic 3D environments. It makes the discussed validation tests highly intractable for the construction planning applications.

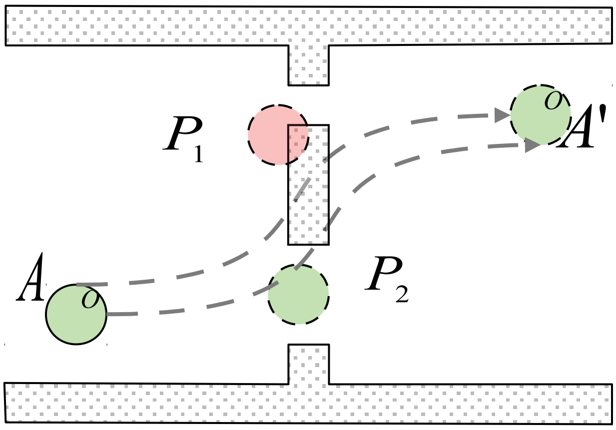

Fig. 6: Path testing example.

Being oriented on exact or approximate metric representations of scenes, the traditional local path planning methods, like configuration spaces, generalized cones, visibility graphs, Voronoi diagrams, probabilistic roadmaps (PRM), rapidly exploring random trees (RRT), potential fields, and cell decompositions have significant limitations in case of large-scale environments. Their inability to use overall priory information on the whole environment creates serious shortcoming in the global planning. Topological schemes try to overcome these drawbacks by representing the original scene environment by means of route graphs. Typically, vertices of such graphs are associated with identifiable locations and edges – with possible routes between them. Topological schemas scale better than metric ones, but being resistant to geometric representation errors may yield incorrect or suboptimal solutions (Lamarche 2009).

Effective computational approach could consist in a combination of topological and metric schemes leveraging both global and local planning strategies. Topological schemes are used for making high-level decisions about perspective routes, and metric schemes – for local correction of routes and their final validation. The approach would provide a whole coverage of complex indoor/outdoor environments and would resolve multiple requests in reasonable time. Some particular methods have been developed in the scope of this approach (Ellips and Davoud 2007). Conducted computational experiments proved their suitability to the discussed validation problems.

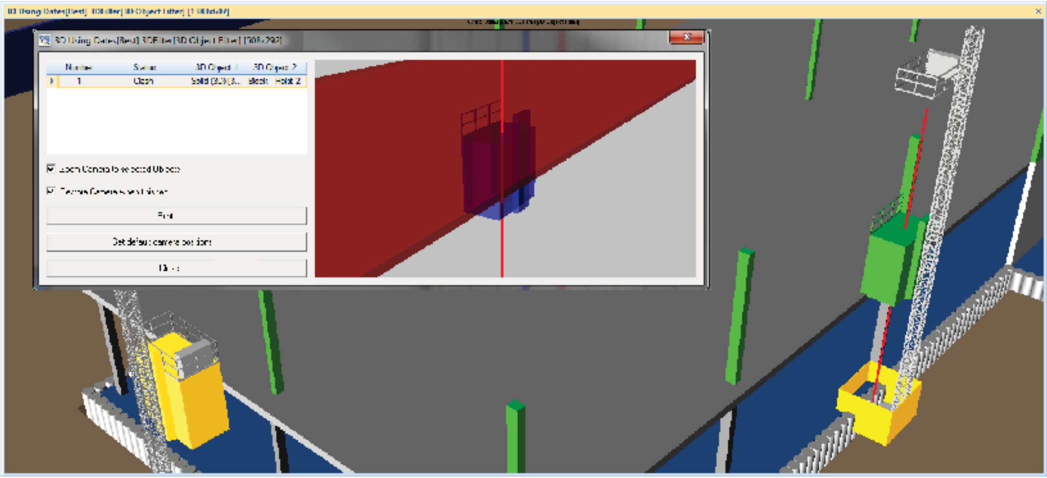

Fig. 7: The application screenshot illustrating path testing.

Finally, Figure 7 shows the detected problem in the project schedule using path testing. It is due to the absence of collision-free path for the lifting equipment that is allowed to move only in a vertical direction. The deployed construction element prevents permissible movements of the lift.

4. Conclusions

Thus, advanced methods for a more comprehensive and trustworthy validation of project schedules have been presented. They assume the extended test suite composed of four complementary groups of checks, namely: clash, join, workspace and path tests. Compared to the usual clash testing, the test suite helps to identify non-trivial defects like missing of supporting neighbouring elements, unavailability of required workspaces and absence of collision-free paths to deliver the elements to the destination locations. For each group of tests the formal mathematical criteria and efficient computational strategies are presented and discussed. It is essential that none of them need detailed specifications of testing use cases and can be applied for large-scale construction projects simulated in the pseudo-dynamic mode. The conducted computational experiments have confirmed the effectiveness and the feasibility of the proposed 4D planning and validation methods, which looks very promising when used in the industry practice.

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DETERMINING THE APPROPRIATE ROLE FOR MIXED REALITY TECHNOLOGIES IN FACILITY MANAGEMENT

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ABSTRACT: *The use of digital technologies in design, construction, and building operation has been increasing in recent years. With the ever increasing amount of information that is being added to digital models of buildings, it is becoming increasingly important to interface that digital data with the physical facility so that facility managers can access applicable information on site to make appropriate decisions over the facility's lifecycle. One way to begin to bridge the information accessibility gap between reality (the physical facility) and virtuality (the building information model) is to use some form of mixed reality. Mixed reality is defined as the mixing of the real and virtual world. This mixing occurs along a virtuality continuum that ranges from nearly 100% reality to nearly 100% virtuality. If implemented properly, this technology could offer significant benefits to building owners for particular facility management use-cases, but thus far, there is a limited comprehensive understanding of what types of mixed reality systems (and under what circumstances) offer the most benefit to facility managers. This paper seeks to address this gap by defining different possible facility management use cases and approaches to using mixed reality technologies to improve the facility management process. To identify these uses, an initial survey of the literature was performed with a content analysis and then an assessment undertaken on how mixed reality may be able to improve current facility management workflows. Then, the current practices of facility managers were identified through interviews with a team of facility managers to determine the information used on a day-to-day basis. Several different suggestions were generated related to ways that mixed reality could offer benefit during facility management. In general the suggestions made fell into three categories: building element information collection, procedural understanding, and building element location/wayfinding. Based on the results of this exercise, different forms of mixed reality were suggested to support high-value implementation strategies in the facility management domain in each of these categories.*

KEYWORDS: *Augmented reality, augmented virtuality, mixed reality, facility management*

1. Introduction

A substantial amount of research related to mixed reality (MR) has been conducted as it relates to design (Dunston et al. 2003, Rekimoto 1996) and construction (Reiners et al. 1998, Shin et al. 2007). While some research has examined how augmented reality (AR) may be able to help facility managers (Lee and Akin 2007), there is less work related specifically to MR in the facility management context. This paper seeks to analyze the types of processes that facility managers undertake and to determine the types of MR interfaces that could help these different tasks in the future. To obtain this information, several facility managers at Penn State's Office of the Physical Plant (OPP) were interviewed to get a better idea of the types of tasks that occur during facility management. The responses were documented and analyzed. Based on prior research about the strengths of MR in different use contexts, suggestions were derived to determine where along the virtuality continuum, as defined by (Milgram and Kishino 1994), solutions may fall for different facility management uses that warrant future research.

Because this paper seeks to highlight many different possible ways that MR could potentially assist facility managers, it was important that the facility managers interviewed be asked questions that would allow them to brainstorm and create as many different ideas for how MR could help facility management as possible. To avoid any potential biases against new technologies or building information models (BIM) in facility management applications from bad prior experiences, the facility managers interviewed were asked questions supposing idealized conditions related to BIM and technology. For example facility managers were asked "How could you foresee using mixed reality to help your future facility management process?" as opposed to asking "From your experience, how would you want to use BIM to create a mixed reality application to aid in facility management?" This type of questioning removes some of the barriers associated with negative prior experiences with BIM. As a result, several different ideas were generated by different facility managers as potential ways that mixed reality could be of value during facility management. This type of questioning helps to start with the end in mind related to further development of mixed reality tools to help facility managers. Then, future work can be completed to determine the best way to modify the current BIM creation process to improve information quality and quantity in BIM to account for the new MR uses.

To offer an understanding of the current state of knowledge related to this research, this paper first presents an overview of background literature on building information models, mixed reality, and the potential benefits of utilizing these technologies to benefit current facility management processes. Then, a discussion of the responses obtained from the facility manager interviews and the processes for classifying the obtained feedback is provided. The limitations of this study are then covered and, finally, conclusions are offered from this research effort.

2. Background

While the topic of mixed reality in facility management has not extensively been researched, a substantial amount of research has been completed on related fields. Building information models (BIMs) have seen increased attention in recent years, especially in the design and construction contexts. There has also been significant research conducted on mixed reality in several different related fields. The literature for these areas has been reviewed and analyzed to determine the key findings that will affect this research effort.

2.1 Building information models

A building information model (BIM) is a digital representation of physical and functional characteristics of a facility (Building-SMART Alliance 2011). In recent years, substantial amounts of digital information have increasingly been incorporated into a project's BIM during design and construction, yet building owners still tend to be one of the less BIM-inclined project participants on a construction project (Bernstein 2010). There are several potential reasons for why owners may be less inclined to opt to use BIM for facility management. Owners may feel that the benefit of BIM is still questionable because it is difficult to quantify the benefit of this technology. There is perceived benefit among industry participants who have "bought-in" to the concept of BIM, but the value of this benefit is much harder to quantify than the costs associated with BIM (Fischer and Kunz 2004). The work of Azhar et al. (2008) strengthens this point by showing that, in a survey of different building projects that used BIM during construction, the return on investment for the different projects ranged from 140% to 39900%. This variability only serves to further cloud the data and confuse industry members, including facility managers, about the quantitative benefits of implementing BIM.

The potential of a mixed reality (MR) application to improve a given facility management process is largely dependent on the digital information that is added for a user. Because BIMs have been gaining attention in recent years, they will likely prove to be one of the greatest sources of digital information for developing MR applications for facility management. However, because BIMs have not traditionally been designed for facility managers' use (Azhar et al. 2008), asking current facility managers how they could foresee using the Building Information Models created on prior projects with a mixed reality interface to improve the current facility management processes would typically yield responses of a reason (or several reasons) why they could not use the prior BIMs. As a result, facility managers tend to underutilize building information during a building's lifecycle because of issues with reliability and accessibility of information (Lee and Akin 2009). This may be an area where structured BIM development guidelines such as that by the Computer Integrated Construction Research Program (2010) at Penn State can help to improve reliability of information and MR can help to improve accessibility of it.

2.2 Defining mixed reality

Mixed reality is defined as the merging of real and virtual worlds along the virtuality continuum (Milgram and Kishino 1994). This continuum, shown in Figure 1, ranges from mostly physical to mostly virtual environments. For instance, mixed reality can be mostly virtual information augmented with some real information, such as a virtual model that is augmented with positioning information from a GPS tracking a building user. This example of mixed reality could be considered to be augmented virtuality. Alternatively, mixed reality could include predominantly real information augmented with some virtual information. For example, in this case, a user could look at a building element with a portable computer display or smartphone and see the physical facility through that device with digital information, such as air flow rates, overlaid on top of the view of the physical element. This example of mixed reality would be considered augmented reality. There are many other potential use-cases that could employ a mixed reality system that would fall somewhere within or outside the examples mentioned on the virtuality continuum. The potential for technology such as this could offer great benefits throughout the building design, construction, and operation phases of a facility's lifecycle.

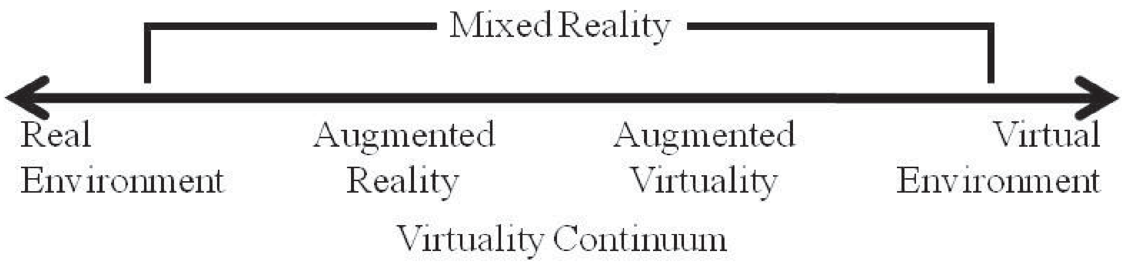

Fig. 1: Milgram and Kishino's (1994) Virtuality Continuum shows the range where mixed reality can fall, from just before completely real and completely virtual environments.

For the most part, mixed reality research, as it relates to facility management, is still in its infancy, but there have been a few research efforts that have begun to look at this tool in the facility management context. Augmented reality computer aided drawing (ARCAD) has been studied to see how it may be applicable for visualizing designs for new construction or renovations in the context of the actual project site (Dunston and Wang 2005). This research suggests that ARCAD can likely improve the cognition of a building design by users over traditional (strictly virtual) methods. Other research also demonstrates the merits of mixed reality for facility management by creating the Augmented Reality-based Operations and Maintenance Fieldwork Facilitator (AROMA-FF), a basic prototype to relay real-time building sensor information, geometry data, and facility management data to users through an augmented reality interface (Lee and Akin 2010). In particular, the work demonstrated that the application created can save facility managers 51% of time on facility management tasks by helping the user locate key building equipment in the facility.

2.3 Analysis of mixed reality techniques

A substantial part of the analysis conducted in this research involves synthesizing appropriate suggestions of how the use of mixed reality can achieve the desired benefit of the different facility management suggestions received during interviews. To create valid suggestions, it is necessary to understand how and when mixed reality is beneficial. In general, when looking at how to automate processes it is important to consider what a particular technology excels at more than the abilities of a human. For automation using robotics and machines, "grunt work" tasks that require repetition, high strength, and completion in a hostile environment make more sense to automate than those that require intense information processing (Everett and Slocum 1994). Similarly, computers tend to be best at informational "grunt work" tasks as well. Computers can quickly search databases, test many simulations with known variables to determine a best option, and complete other tasks that might take a human minutes or hours to complete in a matter of seconds.

In facility management context, much of the work performed requires more than simply retrieving information or running simulations. Managers must intelligently assess a situation, analyze the situation to determine a problem area, and determine an appropriate solution to a problem. The process used to determine a fix to a given problem may vary based on prior experience, the type of problem, context of the problem situation, or location of the problem, to name a few of the many variables. This type of complex process is difficult (with the technology offered today or in the foreseeable future) to completely automate with the use of computers, machines, and technology. Cameras, sensors, and other computational support technology may be able to help the facility managers by providing pertinent information, but it is unlikely that they will be able to completely replace human facility manager. Therefore, as performed in (Dunston and Wang 2011) this work will break down the suggestions received from facility managers to determine how MR could benefit the processes.

3. Facility Manager Interviews

The Pennsylvania State University's Office of the Physical Plant (OPP) is responsible for maintenance and supervision of the university's facilities as well as certain necessary design and construction tasks on campus. OPP has approximately 950 employees, including architects, engineers, and construction experts. This team operates as a support business to maintain the approximately 800 buildings on Penn State's main campus.

3.1 Interviewing facility managers at Penn State's Office of the Physical Plant

Several different facility managers shared their experiences and thoughts related to the potential of some form of mixed reality to their management processes. Three facility managers responsible for handling individual, day-to-day work orders were interviewed as well as the supervisor for area services, who oversaw the work orders for a large portion of Penn State's campus. Because the facility managers interviewed had different schedules and time commitments, the duration of interviews varied from about 10 minutes to about 3 hours. The interviewees' expertise was in specific facility management practices, not MR. Therefore, because many individuals had no prior experience with any form of mixed reality, a brief explanation of MR technology was presented so that they understood the strengths of this technology. Open-ended questions were then asked to the facility managers related to how they felt that this type of MR technology could offer them benefit. They were asked what types of work situations they would want to use this technology and their responses were recorded.

There are, admittedly, limitations in asking a group of people who are relatively unfamiliar with a technology how it could potentially be used to help their workflow. Some suggestions that the facility managers made did not directly relate to the use of MR technology. The key advantage of asking open-ended questions like this, however, is that the responses reflect ideas that would be valuable to the facility managers, even if some ideas do not directly relate to a MR solution. It is important to remember that MR technology is a tool developed to improve the process for completing particular tasks, not the other way around. In other words, the goal should not be to create facility management use-cases where MR would be a perfect fit, if the use case developed is unrealistic.

From the interviews with the facility managers, several different MR-related suggestions were generated. The content obtained from these interviews varied from specific to general. Similar responses were grouped together and others were subdivided into separate responses where appropriate. A summary of their recommendations focused upon:

- Connecting maintenance record history to the onsite building elements;
- Locating ducts/pipes onsite that are visually hidden;
- Linking clients' photographs of a work order to portable MR device to more easily identify problem area in a building;
- Linking facility managers' photographs of prior work to portable MR device to document work completed on a given building element;
- Retrieving operations and maintenance (O&M) manuals, warranties, facility management history, contact info of parties related to a building element, as-built plans, design temperatures/flow rates/pressures of building elements for comparison of current performance against intended design performance, historical commissioning data for building elements;
- Animating emergency maintenance procedures;
- Identifying particular ductwork, pipes, or conduits that a given air handling unit, pump, or panel board feeds;
- Linking room number from customer orders to model/plans to show exactly where a facility manager is and where they need to go;
- Locating emergency shut-off valves and equipment for less-experienced workers;
- Locating building utilities on site and as a facility manager enters the building;
- Updating changes to facility information over building lifecycle; and

- Reducing the duplication of work orders in customer information system.

Much of the feedback generated by the facility managers was created because of bad prior experiences that could have been avoided with proper implementation of the suggestions mentioned. The facility managers shared anecdotes about times when there were problems with locating key building elements and collecting adequate information to troubleshoot work order problems. They also mentioned the potential for documenting or animating certain emergency procedures for less experienced facility managers or for facility managers that may be responding to a building issue during non-work hours when they may go to a building with which they are not familiar.

After the discussions were held to determine how the facility managers might want to use mixed reality, they were also asked to explain the current process that would occur to complete a typical work order. This information assists in determining how MR might be able to tie into the existing workflow. In general, work orders come through a customer information system (CIS). These work orders include basic information about the nature and location of a particular problem. The work orders are prioritized based on the emergency level of the particular work and then assigned to appropriate facility managers in one of several different discipline categories (mechanical, electrical, plumbing, carpentry, etc.) by the supervisor of area services. Once assigned, the facility managers are responsible for completing the work associated with the work order. The specific workflow associated with a given work order varies depending on the type of work that is necessary to complete a task. Frequently it is necessary for facility managers to go to the location of the problem to fully understand the nature of the problem. They may have to ask for or look up information related to prior work performed on the given building element. After collecting the necessary information, they determine the appropriate solution and fix the problem. After the work has been completed, the work order is closed.

From the discussions held with the managers related to current processes, the comment was made that the biggest opportunity for improvement is related to reducing wasted time. It is not uncommon for facility managers to experience a loss in productivity due to unnecessary trips to a job site, uncertainty as to the location of a particular problem, or not choosing the best solution to fix a problem because of inadequate available information. This can be a key area that future work in MR may be able to offer support to the facility management process.

3.2 Analysis of responses

After the responses were received, the different ideas were analyzed to determine the type of information and the most appropriate method(s) for delivering the information to yield the desired benefit. Based on the analysis, an appropriate level of mixed reality was suggested. Figure 2 illustrates where the solutions to address the different use cases are mapped on Milgram and Kishino's virtuality continuum. The different responses are grouped into three categories that summarize the types of responses received. Information collection is related to keeping facility managers aware of all applicable information about a given building element so they can best assess a given situation. Procedural understanding is related to informing facility managers, who may not be as familiar with a particular work flow, the steps to take to mitigate a problematic situation. Building element location and wayfinding is related to providing information about the location of a facility manager in a building, the location of building elements that may not be known to a particular facility manager in a particular facility, or the location of building elements that may be hidden behind a wall or underground. The figure also describes the possible implementation strategies that can be utilized to realize these different solutions in future research and development work.

Several of the suggestions generated in this work are also mentioned in (Lee 2009). This dissertation involved a facility management shadowing activity where four different facility managers in the electrical and plumbing trades were shadowed while they were completing their daily activities. It highlighted the fact that there were several aspects of the shadowing experience where inefficiencies were found. These were primarily related to locating equipment and obtaining proper materials and spare parts to complete a job. The interviews conducted for this research also stressed the importance of locating key building elements and also linking appropriate information to a MR interface to allow facility managers to better assess a particular work order and ensure that they can bring proper materials and tools to complete a given work order.

3.3 Definition of terms

Because this research begins to develop a full spectrum of possible use cases for mixed reality in facility management across the virtuality continuum, a specific set of definitions is used for the different terms in the spectrum. The virtual environment has been defined as an environment consisting solely of virtual objects (Milgram and Kishino 1994). For the context of this analysis, this means that the virtual environment is defined as a computer-based environment that a facility manager could use at his or her office or on a jobsite with the use of a portable computing device or laptop, where all manipulation of building data and computer models is performed manually and no automated prediction of problem context, user location, or any other computer-derived knowledge is incorporated into this context. The real environment has been defined as an environment consisting solely of real objects (Milgram and Kishino 1994). For this context this means that a facility manager's view is in no way incorporated with digital information. Augmented reality has been defined as when the display of an otherwise real environment is augmented with virtual (computer generated) graphics (Milgram and Kishino 1994). In the facility management context this would mean that a user might be viewing a real space through the camera view of a portable computing device and see facility data or geometry superimposed on to the view of the real world geometry in a space. The term augmented virtuality has been defined less concretely as the converse of augmented reality (Milgram and Kishino 1994). In a more specific sense this would mean that AV would be defined as when an environment with a display of an otherwise virtual environment is augmented with real graphics. For the purposes of this research, this definition is insufficient for AV. When adding content from a virtual environment into a view of a real environment, only images/data from the virtual world would be added so the definition for AR is appropriate. For AV, however, there are "reality" aspects other than purely images and graphics that can be added to a virtual environment. For example the reality component could include GPS location information to navigate a model, use of gyroscopes or accelerometers in a field computing devices to allow a user to physically navigate around a virtual environment, or context-aware information retrieval where a computing device may recognize what activity is occurring in the real environment and display appropriate information as a result. Therefore, for the purposes of this research, AV is defined as an environment that is an otherwise virtual display augmented with some aspect of reality.

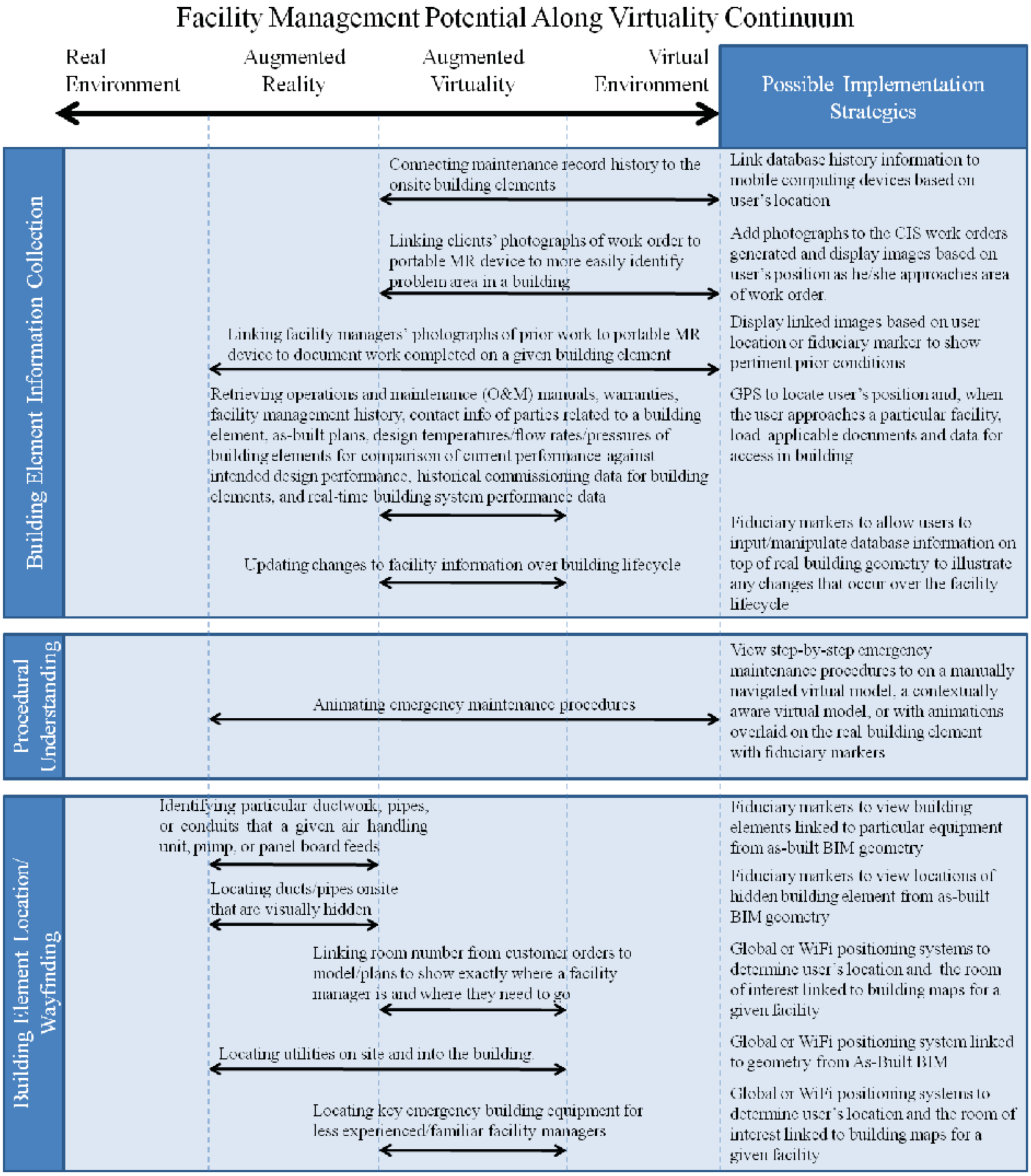

Fig. 2: The mapping of facility manager's responses on to the virtuality continuum.

3.4 Discussion of results

This particular research effort focused on developing a better understanding of the facility management use cases which could benefit from the use of MR and highlighting potential areas for future research and development work. The possible implementation strategies column of Figure 2 was developed to act as an intermediary between the suggestions of the facility managers in the field and the current (and nearly foreseeable future) mixed reality capabilities that may help to realize the suggestions provided by the facility managers. This column should not be seen as the only method for developing a mixed reality facility management solution, but rather as a logical method for realizing a solution given the current state of technology. For example, currently fiduciary markers are a simple, yet powerful, tool for superimposing virtual geometry onto a user's real camera view of a space. Eventually, when other technologies become just as accurate, it will yield other potential solutions for a use case (e.g. WiFi location systems in lieu of marker-based approaches).

Regarding the spread of the solutions shown in Figure 2, it can be seen that there was a range of suggestions made by the facility managers interviewed for this research. Some logical solutions to the feedback received from the facility managers could realistically fall into several categories of mixed reality. Other suggestions would lend themselves more to only one type of mixed reality. While some of the suggestions received could be partially realized in a purely virtual environment, none of the solutions suggested would likely be addressed in a purely real environment. Suggestions that could be solved entirely in the real environment have no need for MR or linking technology to a given process and, therefore, would not apply to this research. While it is true that the purely virtual environment also does not tie directly into mixed reality, it may act as a starting point from which to build on so that it may be eventually incorporated into a mixed reality medium. All suggestions that were related to the virtual environment on the figure shown did still have some possible validity to be incorporated into a mixed reality environment as well.

All feedback received related to suggestions that were pertinent only to the real or virtual environments (and not a MR application) were not included on the figure. For example, a suggestion was made to reduce duplication of work orders in the customer information system. The logical solution to this problem would be a software solution that would be purely in the virtual environment. Since there does not appear to be a logical MR application for this comment, a MR solution was not proposed and it was not included on Figure 2.

3.5 Limitations of Research

First, the work presented here is based on a single case study (OPP at Penn State). More case studies with facility managers in other organizations would be necessary to obtain a more holistic perspective. While this work generated a broad array of feedback for potential methods to improve facility management through the use of MR, there are several challenges and limitations to the results generated from these suggestions. The MR suggestions require some type of digital information for a computer to reference to add to a user's visual experience. In the field of buildings, the most logical source of information would likely be in a Building Information Model (BIM). This has some challenges, however. As stated earlier, BIMs are not typically created with a facility manager's workflows in mind. They are created to improve the design and construction processes. Therefore, some key information would not be contained in the BIMs as they are currently developed. In addition to this, it is difficult to verify the accuracy of a BIM to 100% certainty. For a MR solution to offer benefit to a facility manager in providing better information to allow better problem diagnosis in the field and reduce inefficiencies, it is critical that the information presented to a facility manager be accurate. These challenges will need to be addressed before high value can be realized from the feedback generated in this research.

4. Conclusions

This research focused on identifying specific use cases for mixed reality to improve facility management. As mentioned earlier, areas of inefficiency that waste time during facility management are arguably the most promising area to target future research efforts seeking to improve facility management processes. Therefore, the feedback received from the interviews held with Penn State's OPP facility managers was filtered and analyzed to determine what suggestions could be developed, with the use of MR, to help save time for future work. The responses that related to a MR solution were analyzed and the appropriate level (or levels) of MR were synthesized based on the feedback received from the interviews, the current workflow employed within the owner organization, and the prior relevant research related to MR. These responses fell into three general categories: Building element information collection, procedural understanding, and building element location/wayfinding. They can be seen in figure 2. Therefore, this research suggests that these may be some of the key types of categories to target future work and future application development to realize the greatest impact for facility managers.

This research analysis also suggests that, not only are there several types of use-cases where MR could be a beneficial solution, but there are also several forms of MR that may be able to improve facility management processes. Some use cases indicated in this research may benefit from the use of augmented virtuality as well as augmented reality. Given the level of sophistication of MR technology, some of the use cases that could benefit from multiple forms of MR may need to be tested with the form of MR that is more realistic to create until more advanced systems are developed. It is also likely that in future work, additional uses for MR will be discovered through further exploration of possibilities with other facility managers. These use cases can then be added to the responses generated in this work to create an even more comprehensive understanding of facility management.

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AUGMENTED REALITY IN ARCHITECTURE: DEVELOPMENT OF CRITERIA FOR CREATING ADAPTIVE EDUCATIONAL ENVIRONMENT

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ABSTRACT: *This paper focuses on reviewing Augmented Reality (AR) technologies that aim to optimize the use of limited spaces with limited physical characteristics, caused by the application of traditional means (i.e. actual construction or redesign work) in higher education. There are many compelling examples of AR being used for educational software, and this paper will also focus on the potential of AR to optimize the use of learning spaces through transforming their functionality. The study aims to suggest suitable applications to provide adaptive learning opportunities for classroom occupants. The paper will discuss the features of mono-functional (spaces with only one application) and multi-functional (spaces with more than one application)in order to review the relevance of the application of AR in architecture. Two case studies that deal with the underlying software and hardware requirements will be reviewed in order to support or refute theories on the ability to adapt educational environments through the application of AR. Recently, those working in the field have promoted the concept of flexibility, i.e. the possibility of AR being used for architectural design and visualization practices. Ideas presented are based on reviewing AR applications in corresponding literature sources. This research considers the adaptation of AR for architectural purposes in educational centers with a view to improving the usability of the space and will contribute towards further realizing the potential of AR techniques through comparison of the two case studies.*

KEYWORDS: *Educational Environment, Augmented Reality, Mono-functional Spaces, Multi-functional Space.*

1. Introduction

As colleges deal with issues such as a new generation of students, as well as changing technologies, the effective use of space is becoming a significant issue in higher educational facilities (Steelcase, 2011). However, classrooms are often not designed with specific educational activities in mind. Likewise, current educational spaces are not flexible enough to allow for a variety of activities (O'Neill, 2009). The structures have not been created in terms of this new paradigm in institutional design, or in terms of computer-based organizations (Streitz, 1998). This paper intends to address the application of AR in architectural space and the creation of visual transformations to provide more functionality to existing educational spaces. It is hoped that this new functionality will create flexible classrooms, and optimize the uses of learning space. Recent studies indicate that building transformation is attempting to provide more versatile characteristics to mono-functional spaces. This transformation will aim to create multi-functional spaces where previously only mono-functional ones existed (De Jonge, 2009).

1.1 Research Background

Current educational spaces cannot be easily adapted for a range of learning activities and courses (Steelcase, 2011). This has led designers and researchers to consider redesigning classrooms to respond to the requirements of eco-friendly technology that enhances interactive learning (Maria et al. 1999). The current design of classrooms in universities is mostly mono-functional and it is important to design spaces that can be used by different groups in different ways (Chism, 2006). The use of AR to optimize the functionality of spaces has been inspired by the concept of cooperative rooms (Streitz, 1998).

1.2 AR Technology

AR can be defined as an environment in which a real world context is dynamically superimposed in a virtual context (Azuma, 2001), According to Frederick Brooks (1995), 'AR is a specific example of *Intelligence Amplification* (IA): when humans use computers to make tasks easier' (Frederick, 1996).

AR combines the real world and a synthetic environment and allows the user to see reality upon the virtual objects and environment. It also creates the sensation that virtual objects are present in the real world (Cawood, 2007). Since the first AR interface was developed by Sutherland in the 1960s, a number of applications have been explored and various researches have been carried out (Azuma, 1997). Virtual reality completely immerses the user inside a synthetic environment and does not allow him or her to see their surroundings in the physical world (Sutherland, 1965). On the other hand, AR enables the user to see the virtual object super-imposed upon the real world. AR therefore attempts to enhance reality rather than replacing it (Kaufmann, 2010).

2. Features of AR

AR has a vast range of potential applications, including include medicine, manufacturing, urban planning, and many others (Azuma, 2001). The ability to visualize the design for an actual site or building also means that AR can have a great impact on architecture. This paper will focus on the application of AR in actual space. According to Korgh (2001) 'Applying AR in architectural rooms is something beyond a complete interaction with digital technology.' Below are the five common types of AR (Savoie, 2010).

- **Projection**
  Interactive on any flat screen, this application is the most common type of AR.
- **Recognition**
  The recognition of shapes or actual items in order to provide the user with real time information.
- **Location**
  Determining a position superimposed over a live image, and directing the user toward his destination.
- **Outline**
  Blending the outline or a part of user's body with virtual objects, allowing him or her to hold objects and manipulate them, while a user controls it with an outline of him or herself.
- **Hologram**
  Users may see a spinning or smoke mirror in real space which allows them interact with a camera-based system, tracking real world impulses (Hayes, 2009).

2.1 Techniques of AR

This section will discuss the three computer vision techniques applied during research: tracking techniques, detection, and rendering.

2.1.1 Detection

Marker detection is a very important component of marker-based in AR. If the marker is not detected, objects cannot be augmented (Ahyun et al. 2010). The proposed procedure enables camera tracking even in the event that the marker goes out of the sensing range or is hidden by an object. The algorithm is relatively simple and is useful in a variety of applications (Parhizkar, 2010).

2.1.2 Tracking

Although tracking technology presents some issues for AR in general (Azuma, 2001), it has been the most popular area of research. This is due to the fact that it is one of the fundamental enabling techniques utilized in augmented reality (O'Neill, 2009).There are three tracking techniques applied in AR: Sensor-based, vision-based and hybrid tracking systems which have been applied in many recent projects (Homero, 2006). In this research, we will consider a hybrid tracking system. In the early stages of research on hybrid tracking, Azuma (1997) built a hybrid tracking system by combining optical and magnetic tracking which was faster than standalone optical tracking systems, and outperformed a magnetic system in terms of accuracy and jitter (Thomas et al. 1999).

2.1.3 Rendering

Using visual markers in AR systems depends largely on the tracking system for visual marker detection, tracking and pose estimation (Xiang et al. 2000). A typical AR system uses a display and a motion tracker with the associated software. The software reads the tracking events to discover the position of the display and then renders the virtual objects. In order to render accurately, the virtual objects and the real world need to be registered. This registration implies that the virtual camera where the augmentation is taking place has a known geometry and can be tracked in the real world (Feng et al. 2008). In AR, real-time rendering is required, and system latency may decrease rendering performance (Parhizkar, 2010). Color images require more memory, and more time in order to manipulate the image for detection. This also reduces rendering performance. It is likely that there will be a considerable number of spread and networked data devices employed, a concept dubbed 'ubiquitous computing' (Wister, 1991). Wister's concept allows for some invisible devices that are embedded in the environment, and some that are recognized as computers. The 'Roomware concept' has been inspired by AR research and utilizes computer-augmented objects that are formed from integrating room elements and furniture such as walls, doors, tables and chairs, with computer-based information devices. These devices provide support for the creation, editing and presentation of information. They are networked and therefore have access to worldwide information as well as the architectural components of buildings (Streitz, 1998).

3. Potential of Learning Application in Actual Space

With the advancement of AR technology in space design, architecture is becoming more responsive and ultimately adaptive (Mackay, 1999). In fact, through applying AR, occupants pay a different kind of attention to designs. Computer-augmented environments should enable designers to create practical interfaces in actual and virtual everyday use (Streitz, 1998). AR may also open possibilities for direct experimentation from different viewpoints (Steelcase, 2011). AR and other virtual digital displays can revolutionize the way occupants interact with architectural spaces (Mackay, 1999).

AR can be seen as part of the atmosphere, and allows the designer to select objects to include in the design (Steelcase, 2011). AR supplies us with not only a new functionality, but also is a part of a new way of working in design and architecture (Steelcase, 2011). Applying AR in Architecture is a suitable method for interacting with and enhancing architectural rooms rather than simply relying on digital technology. It also results in a more artistic effect of space, due to increased integration between users and their perception of the environment where digital technologies are incorporated (Steelcase, 2011).

3.1 Application of AR in Architecture

This research uses AR to connect physical and digital objects in an educational space through case models. The case models studied contain information on relating ideas to other AR projects. This will provide a platform to support possibilities for applying AR to optimize the use of architectural spaces.

The approach focuses on reviewing case models in multiple contexts in order to propose theories regarding the platform. The idea of optimizing the functionality of mono-functional spaces has been inspired by developed designs such as Azuma's *"Virtual furniture in real Environment"* in 1997, and *"Interactive Rooms"* by Peter G. Krogh, Architect in 1999. The findings of the two AR applications to support the potential of this platform are discussed here.

3.1.1 Virtual Furniture in Real Space

According to Azuma, (1997) AR is a variation of Virtual Environments (VE) (Milgram 1994). VE technologies completely immerse a user inside a synthetic environment where the user is unable to see the real world. On the other hand, AR allows the user to interact with the actual world and with virtual objects superimposed upon or composited with the real world. Ideally, it would appear to the user that virtual and real objects coexist in the same space (Durlach, 1995). For an instance, a real desk can be seen with virtual accessories, a virtual chair can be located behind the table, and a virtual lamp located on the table in accurate proportions. The objects' locations are created through AR and are therefore displayed in 3D (Azuma, 1997). Figure 2 shows an example of this. AR can be thought of as the "middle ground" between VE (completely synthetic) and telepresence (completely real), (Milgram 1994). It is also possible to add and remove objects in a real environment. For example, it is possible to remove a desk in the real environment, draw a picture of the real walls and floors behind the desk, and effectively remove it from the user's sight (Milgram 1994).

Analysis of the afore-mentioned project shows that there are some difficulties and limitations, the registration plans mainly concentrated on a single plan, and were not able to avoid registration errors (Young, 1998). The accurate alignment of objects in real and virtual objects is significant and complicated (Parhizkar, 2010).

Focus and contrast are other challenging issues of AR application in real rooms. In the optical case, the virtual image is projected a certain distance away from the user. Although this distance is usually fixed, it may also be possible to adjust it (Holloway, 1995). However, even if the actual objects are at various distances from the user's location, the virtual objects are all projected to the same distance (Azuma, 1993). If virtual and actual distances are not harmonized, viewing both virtual and real objects at the same time might not be possible (Azuma, 1997).

Fig. 1: A Real desk with virtual lamp and two virtual chairs
Source: (Azuma, 1997).

3.1.2 "Interactive rooms"

The second case model is *"Interactive rooms"*. In 1999, department of communication design from the Univerisity of Aarhus, developed a course named 'Interactive Rooms' in collaboration with Kaj Gronbak from Inter Media. According to Peter G. Krogh architect (1999), "interactive rooms" contains a series of projects that presented ideas from installation to development of the work environment. The projects succeeded in prototypes related to real physical objects in scale 1:1. During the course of the projects, two interpretations of AR application were applied, initially the combination of the physical and the digital environment, and secondly the use of digital objects as an individual part of the environment (Streitz, 1998).

The aim of these projects was to focus on the improvement of work situations through digital equipment and objects, while attempting not to bring abstract procedures into the work. The use of traditional interfaces was an obstacle that disrupted the necessary focus on carrying out tasks. The project's procedures established interaction with the digital technologies, through the handling of paper and cards, whereas normally people would use these entities by writing on paper, stacking paper, unfolding paper etc. The actual systemizing of physical objects resulted in a constant updated digital version which allowed the process to continue uninterrupted (Wellner et al. 1993). Central to the idea of "Interactive Rooms" was a concern about keeping the digital world individual in the physical environment, in consideration of the fact that digital objects are not merely limited to the virtuality but can, and eventually will be a part of everyday life (Ecrim, 1997). This integration of virtual and physical could change user's movements and consequently modify the expression of the room. The main goal was to create an atmosphere that would allow users to see the potential of merging the virtual world and actual environments (Fischer, 2005).

Methods used in Interactive Room:

The method of this project is based on the most efficient way of working with interactive rooms. It is named "scenarios", largely because scenarios occur as sequences of events happening over time (Kyng, 1991). Several projects during this course were based on video registration (Myers, 1992), a process where virtual objects are aligned with the real environment in order to generate an AR scene. Video techniques for participatory design included observation, brainstorming and Prototyping. Based on this method, mock-ups were designed in both miniature and full scale. The progression proved that it is better to work with full-scale mock-ups to certify the impression of applied AR in physical rooms and objects (Myers, 1992).

Based on the afore-mentioned projects, the virtual furniture in actual space, the coexisting of completely synthetic and completely real environments in full scale, connect physical and digital objects in an educational space. The methods that were carried out in these two case models provide a platform to support the possibilities for applying AR to optimize the use of architectural spaces. There is a need to evaluate the usefulness of this application, since the idea behind this project is complex, scenarios cannot be evaluated with traditional scientific analysis. Often they can be captured and solved in one principal design based on careful analysis (Streitz, 1998).

The most attractive feature of AR in architecture is that it can seamlessly merge virtual objects in a real environment. Explaining the two cases above, we can consider two aspects that can be further developed in future studies. Firstly we could consider a full project that is equipped with a full-scale set of furniture, components and resources that allows for a change to the sense of the space in educational centers. The aim of this article, which is the promotion of multi-functional spaces, can be achieved through the development of a set of registered (aligned) virtual objects in a quick and efficient way. This will allow for objects that can be changed immediately on-demand into different pieces of furniture. However, to achieve this, we must be able to create accurately aligned and registered objects. The two projects discussed in this article mainly support the necessity of having a set of virtual furniture in a real environment. In the first project virtual furniture in real space, the feasibility of utilizing virtual furniture through appropriate AR application was supported by Azuma 1997, while in the latter the main objective was to create an environment where users could experience the merging of the virtual world and actual environments in full scale (Fischer, 2005).

4. Basic Requirements of AR in Educational Applications

4.1 Adaptive Educational Environment

Whilst learning can take place in almost any environment, it is the responsibility of educators to create structures that support learning in a technical manner. Efficiently designed learning spaces can greatly improve learning. Applying radical flexibility can be defined as releasing students from the physical limitations of the traditional classroom by changing the space into a highly adaptable classroom. These changes can support changing pedagogical needs. Adaptive classrooms are defined as the use of the same classrooms for different courses with different needs. In addition, teachers' styles differ so learning activities may vary within the classroom. A variety of functionality in classrooms is necessary to support multiple learning activities, classes with a flexible set up, and that provides a strong relationship between technology and space (Steelcase, 2011). Figure 2 shows the theoretical framework of this study. The diagram indicates the application of AR in architecture functionality, dividing the environment into virtual Environment (VE) (Milgram, 1994) and actual environment. In VE development, the factors of space arrangement, related courses, and space adjacencies to learning activities are considered, while in actual environments the size of classrooms and class layout are the main factors (Steelcase, 2011). The idea of the optimal use of space in classrooms is proposed in this graph. Knowing the characteristics of mono-functional and multi-functional environments will help us to identify the suitable AR techniques for the educational environment (Steelcase, 2011).

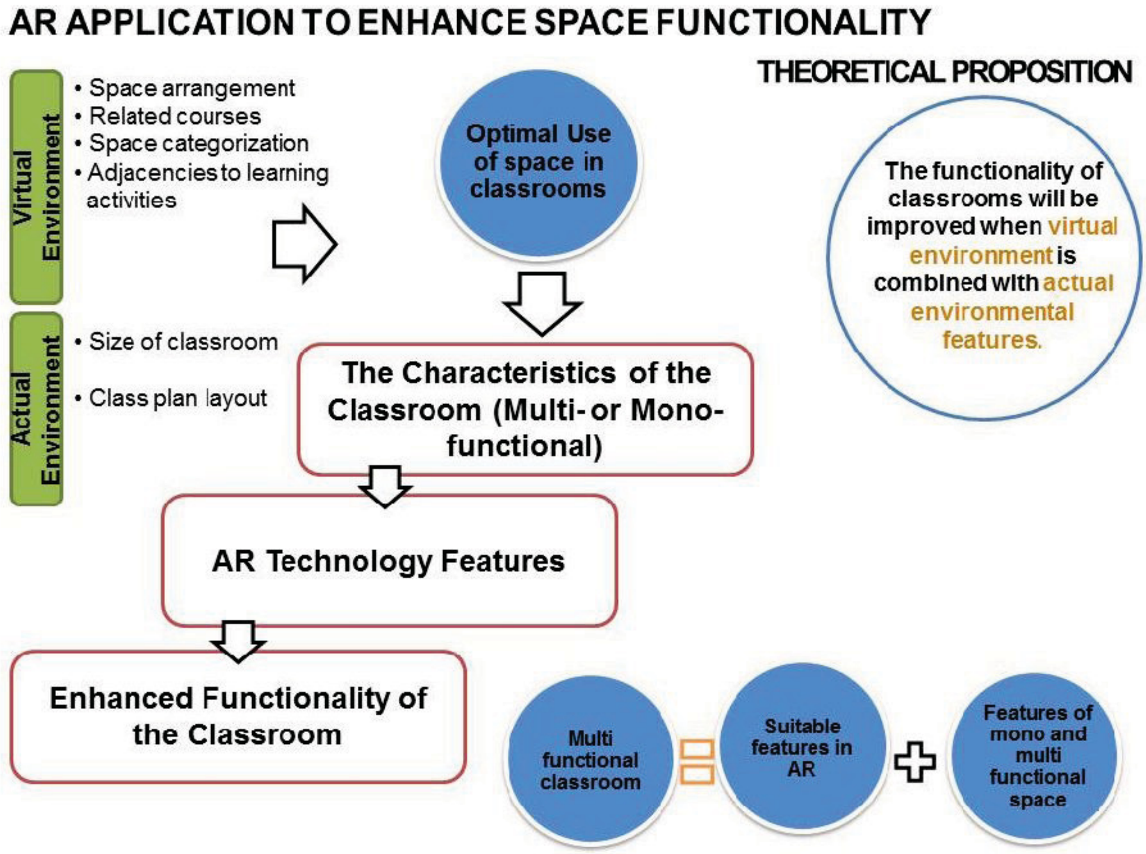

Fig. 2: Theoretical Framework

4.2 Hardware and Software Requirements

There is a wide variety of software and hardware that is required to implement AR in the classroom. These include devices such as HMD webcams and, mobile cams that are mostly used to allow users to see the real world with virtual objects superimposed (Parhizkar, 2010). Software such as Action Script with Flash libraries, *FLARToolkit* (Flash Augmented Reality Toolkit) are often used as an open source for building AR applications in Flash and Paper vision 3D libraries, as well as *Adobe Flex Builder. Blender*, primarily an animation software, is used to animate objects in 3D. The topic objects are imported into *Flex Builder.* Once the objects are imported, Paper vision, 3D libraries are used to rotate, zoom in/out, add color and text, the images can be projected on large screens (Medicherla et al. 2010a). The user is then able to see virtual objects with the aid of *FLARToolkit* combined with Paper vision 3D. The applications are then demonstrated and tested by a webcam. The result demonstrates how marker recognition can augment 3D models directly onto screens. Initial data gathered from students and educators have shown that AR application is a highly portable system, which may have significant benefits in teaching and improving teaching and learning quality.

FLARToolKit Marker Generator is used to save the marker as a pattern file. The FLARToolkit detects and augments the 3D model through this pattern file. *Adobe Flex Builder* is a development tool which is used for coding and designing Internet and desktop applications, it also can be applied to create the AR application for the web (Medicherla et al. 2010b).

5. AR as an Educational Tool

The main intention of an educational environment is to develop a social collaboration among users of a space (Roussos, 1999). Various users may access a shared space populated by virtual objects in a collaborative manner while remaining in real time.

Studies have shown that AR application allows multiple users to share a virtual space. Learners wear head-mounted displays that superimpose computer-generated images on to the actual environment. One of the most common pieces of software used for AR is the SMART System of augmented reality for teaching, an educational system which was designed in Portugal by Rubina Freitas and Pedro Campos in 2008 (Medicherla et al. 2010b). This system was used for second grade-level school based on concepts such as the means of transportation of various types of animals. This system superimposes three dimensional models and prototypes such as a car, track and airplane in real time video which is displayed to the whole class. Knowing that many children play digital games, game-based learning is one way to involve children in learning (Medicherla et al. 2010b). Rubina Freitas and Pedro Campos conducted various experiments with 54 students (32 females and 22 males). The results indicated that SMART greatly motivates students and can have a positive impact on the learning process, especially with less academically successful students (Medicherla et al. 2010a).

5.1 The Potential of AR in Educational Environments

New technologies in educational environments may enable different users to have consistent access to information during the learning process. However, there is a reluctance for construction companies to make adjustments in their designs (Oloufa, 1993). To fully enhance educational spaces, it is necessary to consider applying technological solutions to class activities. It will therefore be possible to create an adaptive educational environment (Lehman, 2010). In recognition of the necessity of increasing student participation in learning activities educators are changing teaching methods. They are therefore looking towards technological solutions to increase the effectiveness of the learning process, both physically and technologically. It is here that we must consider the application of AR to improve existing physical spaces (Lehman, 2010). We must first look to the classroom. As stated in The New Media Consortium and Education Report 2010, the use of AR will increase over the next few years. Therefore, there is a clear need to utilize AR to transform mono-functional spaces into multi-functional ones and allow single classrooms to be used for a range of functions.

5.2 Advantage and Disadvantages of AR in Education

AR plays a significant role in building a connection between virtual and real worlds. Architecture and the built environment is playing a new role in people's lives because of technological advancements and can link users with the real world (Lehman, 2010). This information allows users to experience new places from a distance. This is an advantage when looking at architecture from both aesthetic and functional aspects (Temple, 2008). Research has revealed that the educational value of an AR system is high and can provide additional motivation for students (Freitas et al. 2008).

Usability testing of the AR system in schools has been carried out by researchers (Balog et al. 2007) and both qualitative and quantitative research indicates that this system requires cost-effective support for the users (Medicherla et al. 2010b).

5.3 Value of Employing AR in Education

Domain specifics, pedagogical and psychological aspects have to be considered for the development of any educational technology application (Kuafmann, 2010). Undoubtedly there is no single technology that fits all needs. Appliance of AR is a suitable technique for educational purposes, because it gives users a natural means of communication. Another important psychological factor is that that some users may feel unsafe if the view is 'Locked' in an immersive VE, whereas AR provides a chance to 'keep control' and to see the actual environment around the user. In collaborative mobile systems there is no concern over safety issues as AR allows users to move around freely. There is therefore a full interplay between emotions and learning (Kort, 2001). However these are issues that must be considered by AR system developers when building their ideal learning environment. It is very important that user interfaces and display types be suitable for the educational purposes. For instance, an application teaching blind people the geometric forms of famous architectural buildings should use appropriate input and output devices (Kuafmann, 2010). Whilst we have seen a number of research learning systems that have been developed, AR in educational facilities is still in its infancy (Medicherla et al. 2010a). AR classrooms (Liu, 2007) and AR games (Schrier, 2006) have also been developed to teach in the twenty-first century. Results of these studies suggest that AR systems can motivate, entertain, and engage students with the learning environments.

The efficiency and success of AR in enhancing education quality still requires further research. After the development of AR system design stages, qualitative and quantitative evaluation of the level of involvement is required. In addition, we must also consider the integration of AR systems with traditional teaching methods and pedagogy.

6. Results and Conclusion

AR can enhance the user's immersive experience of human-computer interaction and provide an innovative avenue for the user's perception of the real world. By its very nature AR may be able to bridge the gap between physical and digital environments, but it can only exist through the interaction of virtual and real environments. AR can therefore be seen as a sort of atmosphere, a category, which it is possible to conceptualize and design. Following this, the designer can decide what objects should be part of the concept in order to fulfill the design intentions to provide the functionality needed in educational centers. Due to the many technical challenges and the techniques in AR, it remains an active and interesting research area of computer science and information technology (Whyte, 2002).

It is important to note that the use of AR in architecture using a particular type of virtual furniture in a room requires two crucial realizations: first, the virtual objects must support various functions; second, the respective items must be seamlessly registered. To create an appropriate set of objects in the room, e.g. workshop, classroom, studio, the types of furniture and tools need to be designed and selected. This is crucial and can have a broad impact on the expression of the functionality of classrooms in educational centers.

7. Future Directions

Giorgio De Michelisin, (2000) attempted to typify AR application into two patterns, named *Strong* and *Weak* AR. *Strong* applications often make the occupants feel as if they are in a different place, unlike *Weak* applications, which do not provide a sense of change to the environment. De Michelis' project (carried out in 2000) offers various configurations of the architectural components of AR. The ultimate goal of this study will be the generation of realistic virtual objects that are almost indistinguishable from the physical environment. The development of a system to match different cooperation scenarios with various furniture and configurations on particular types of space function is a major part of future research development. Also, it will be of value to look at other case models, which may introduce suitable AR approaches to architecture with virtual roomware components. This will greatly help this study in identifying the requirements of software to be developed in the future.

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VERTICAL TRIANGULATION WITH A FISH-EYE CAMERA FOR INSOLATION SURVEY

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ABSTRACT: *This paper describes a simple three-dimensional measurement scheme which has good mobility and is suitable for insolation survey. Using a fish-eye camera, a 180 degrees wide view angle image can be taken by a single photo shooting. We use a pair of fish-eye photos for performing triangulation to acquirer height and distance distribution of surroundings so that the visibility of the solar trajectory can be examined. Vertically changing the camera position, the proposed method allows simple setup occupying only small space. Since three-dimensional geometry information is available in the proposed method, even measurement at a single point works effectively for checking obstacles for sunshine reach in the vicinity area, such as rooftops of houses, which gather more and more attention for installing solar power units lately. This paper shows a suitable fish-eye camera calibration method for achieving the vertical triangulation in on-site works. Parallel pattern targets can be used for calibrating both the view angle range and the orientation of the camera. By image processing for finding the vanishing points of projected parallel lines in the image, the view angle calibration is supposed to be done only once before measurement and the orientation calibration can be done any time in a post process. The experimental results showed that the proposed scheme works well and is easily integrated to insolation information including the solar trajectory and sky-dome radiation distribution.*

KEYWORDS: *Vertical Triangulation, Fish-Eye camera, Spherical image, Insolation estimation, Camera Calibration.*

1. Introduction

Coupled with higher population density and urbanization, verticalization of residential buildings has become popular in many major cities. The sudden appearances of high-rise apartment buildings in existing residential areas are often problematic in terms of the impairment of scenery, perspective occlusions, and insulation matters. From the point of view of energy consumption, while solar energy is one of the major alternative power resources, residential building rooftops also receive more and more attention by playing a significant role in the deployment of solar technology, especially when considering the threats of nuclear accidents. However, it is clear that the high-rise buildings can be inevitable obstacles that interrupt the sunshine from many other lower rooftops in dense residential area. Therefore, it is desirable to examine the quantitative accesses of solar radiation to each building rooftop and the efficiency before solar unit installation. In essence, the insolation conditions are different for every point on an each roof surface. The sun changes its position over short and long scale of time period. Therefore insulation survey must cover the spatio-temporal distribution of solar radiation on the surface within the target surfaces. This paper proposes an obstacle measurement scheme for insulation survey by employing simple triangulation with a fish-eye camera to effectively capture three-dimensional (3D) geometrical surrounding's height distribution. Generally speaking, any kinds of terrestrial objects could be possible shading obstacles, depending on 3D geometry. Considering the complex-shaped objects such as trees nearby, image-based 3D measurement has a good potential for capturing the geometrical conditions of them, comparing ranging method using point-by-point targeting.

2. Related Work

Using a camera with a fish-eye conversion lens, wide-angle views can be captured as spherical images. Therefore, fish-eye images have been used often for recording sky-dome images to investigate the solar radiation situation in forest ecosystems. Schwalbe uses a hemispheric image modeling technique to determine the solar radiation distribution on the ground level (Schwalbe 2009). Fish-eye images are used for segmenting the open-sky regions and the occluded regions with tree shades to estimate solar radiation. Yamashita also uses hemisphere photos taken in a temporal series to record the cloud distribution on the sky-dome and its solar radiation (Yamashita 2004). A single sky-dome image shows light distribution from a single viewpoint where the photo is taken. Tomori conducted triangulation based on two images taken from two different ground positions. Triangulation provides 3D surrounding information that allows one to survey multiple interest points in the 3D space (Tomori 2000). Tomori uses the same scheme as normal stereo-camera triangulation to calculate the nearby buildings' height and distance, which can be used for estimating the shaded area on the ground. One of the key aspects for accuracy is the setup of two different camera positions. Normally, the stereo-image measurement quality significantly depends on the camera setup, including initializing the relative camera positions and orientations. Especially in outdoor situations, ground height and inclination vary over the positions; therefore, adjusting and measuring relative camera setups are important and troublesome in on-site work.

3. Proposed Approach

3.1 Overview

We propose a simple on-site triangulation method that can be used for estimating a 3D shading condition by vertically changing the fish-eye camera positions. By changing only the vertical position of the camera one can take multiple photos easily, just by changing the tripod height, for instance. The advantages of this method are as follows:

- requires only a small space and single position for measurement
- simple physical setup and thus correct device initialization
- easy to find the corresponding points of the target between the pair of images for triangulation

This paper also provides an image correction scheme required for achieving the vertical triangulation to assure the advantages shown above. Finally, this paper shows the feasibility of the proposed scheme, which uses the following steps:

1. calibrating angle range of the camera view

2. taking two fish-eye photos at different camera heights with correction target for camera orientation
3. converting images to correct the principle axis and angle of view
4. calculating the heights of the surroundings by triangulation with corresponding points between 2 images

The details of the each step is described in the following subsections.

3.2 Camera Calibration based on Sphere Space Mapping

3.2.1 Intrinsic Camera Parameters

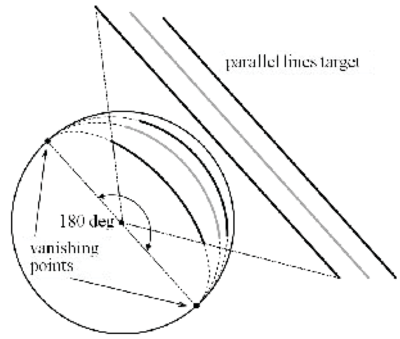


Fig. 1: Parallel lines are mapped onto a sphere space as great circles and show a pair of vanishing points of 180 degrees view.

Our calibration for the angle range of the camera view is based on Li's method which uses a target image pattern of parallel lines (Li 2004). Parallel lines are mapped as great circles onto a sphere space. A pair of cross points of the great circles indicate the vanishing points which are vertical to the principle axis of the camera or the camera direction as shown in Fig. 1. Over 180 degrees view is captured on a wide-angle view of fish-eye image, and thus finding the two cross points and measuring the distance between them tells the radius on the circled image of 180 degrees view. To find the cross points, we fit ellipsoid curves to the great circles projected on the image and extrapolate them. This process specifies the principle axis direction of the camera as the image center, and 180 degrees range as the maximum radius of the circled image. This view angle range calibration is needed only one time for the set of the camera and the fish-eye lens before on-site measurement.

Fig. 2: Image target for the intrinsic camera parameter calibration. A parallel black and white pattern is prepared as a target (left) and is captured through the fish-eye camera which is to be calibrated (right).

A printed black and white parallel pattern is captured by the fish-eye camera so that the parallel lines fill the entire image screen. Fig.2 shows that the parallel lines (left) are captured as a set of curved lines (right) of mapped great circles. Since around the 180 degrees view looks over infinite distant directions that the target pattern does not physically cover, finding the cross points requires extrapolation of the curved lines. We try to fit a quadratic form of the curve represented by equation (1) to each curve. We extract the curves as a set of pixel points on the contrast edge lines in the captured image using image filtering for edge detection. (Fig. 3) To obtain the coefficients of the equation (1) that fit curve to the extracted edge points, we conduct unconstrained multivariable optimization for minimizing the error function (2) by using a derivative-free method in MATLAB (MathWorks inc.) function set. After acquiring a set of fit curves, a pair of the vanishing points are also found as two intersection points by searching the nearest points on the curve set. Then the distance between the vanishing points the diameter of the 180 degrees view on the circled image and the midpoint corresponds to the viewing direction of the camera.

$$a_1x^2 + a_2xy + a_3y^2 + a_4x + a_5y + a_6 = 0 \quad (1$$

$$\sum_i (a_1x_i^2 + a_2x_iy_i + a_3y_i^2 + a_4x_i + a_5y_i + a_6)^2 \quad (2)$$

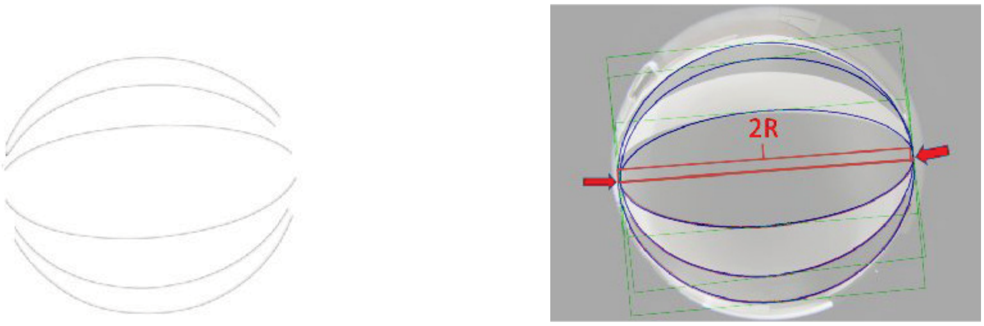


Fig. 3: Extracted parallel lines of B/W boundaries (left) and the fitting result for 5 curved lines (right) Two arrows indicate the pair of vanishing points as the intersections of the extrapolated curves.

3.2.2 Camera Posture

When capturing sky-dome images, precise setup of the principal axis direction of the camera is important for integrating the camera coordinates and the solar trajectory for further process to examine the solar radiation. To avoid troublesome on-site adjustment work for achieving physically consistent camera setup to face the camera vertically upward, we also prepare physical perpendicular targets using several pendulums. This allows a logical camera orientation correction even after the data acquisition. The still pendulums' lines can be extrapolated on the fish-eye image and their intersection indicates the vanishing point toward the physically perpendicular direction as shown in Fig. 4. Fig 5 shows how to show the perpendicular target lines to a fisheye camera, using simple plumb lines made with threads and coins. In this case, the camera is supposed to be placed facing roughly upward and thus the parallel perpendicular lines are captured as almost straight lines and their intersection point can be easily found around the center of the image.

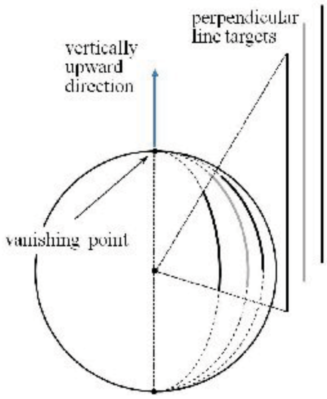


Fig. 4: vertically upward direction target

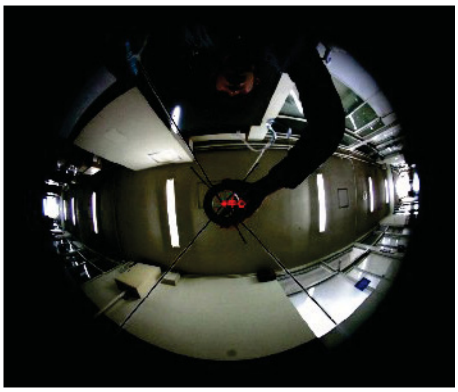


Fig. 5: Setup for vertically upward direction target and captured image example

Next, we can correct the principal axis direction by converting the image so the center is matched to the vanishing point. This process can be done by mapping the image into the sphere space and then changing the orientation in 3D space, and finally mapping back onto the image plane. As depicted in Fig. 6 (left), the vertical upward direction is supposed to be captured at the position of $\boldsymbol{p}_c$ with the bearing angle α relative to the $\boldsymbol{X}$ axis, and displacement $\boldsymbol{r}$ from the image center $\boldsymbol{p}_o$. Three-dimensional correction of the camera orientation is done by finding two axes rotation α and β so that the vertical upward dire ction comes to the image center. The parameter α is calculated as an tangential angle using the coordinates of $\boldsymbol{p_o}$ ($\boldsymbol{x_o, y_o}$) and $\boldsymbol{p_c}$ ($\boldsymbol{x_c, y_c}$) as shown in equation (3).

$$\alpha = \tan^{-1}\left(\frac{y_o - y_c}{x_o - x_c}\right) \tag{3}$$

The fish-eye lens that we use for this research performs equisolid angle projection for imaging. The projection model is difined by the relation between image height $\boldsymbol{r}$ and zenithal angle β as shown in Fig. 7. In the case of equisolid angle projection, the model is represented by equation (4). Then the parameter β is calculated by the equation (5).

Fig. 6: Parameters for camera orientation correction in the image plane (left) and in sphere space (right)

$$\frac{r}{R} = \sqrt{2}\sin\left(\frac{\beta}{2}\right) \tag{4}$$

$$\beta = 2 \cdot \sin^{-1}\left(\frac{r}{\sqrt{2} \cdot R}\right) \tag{5}$$

Rotating angle $-\alpha$ respect to Z-axis then rotating $-\beta$ respect to Y-axis aligns the vector $\boldsymbol{OP_c}$ to Z-axis. This rotational transform is represented as equation (6).

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{6}$$

where, $[X \quad Y \quad Z]^T$ is the incoming light direction respect to $\boldsymbol{P_c}$ whose values are calculated as shown in equations (7).

$$\begin{aligned} X &= \sin\beta \cdot \cos\alpha \\ Y &= \sin\beta \cdot \sin\alpha \\ Z &= \cos\beta \end{aligned} \tag{7}$$

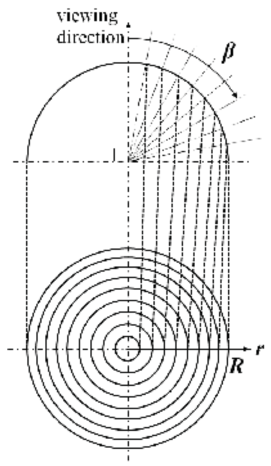


Fig. 7: image height and zenithal angle relation in fish-eye projection (equisolid angle projection model)

where, since only the direction is concerned, the vector norm is arbitrary. According to the image center correction, all the other pixels can be rotated angle $-\alpha$ respect to Z-axis and angle $-\beta$ respect to Y-axis in the same manner, after computing the direction vectors for each pixel based on the displacement from the image center and the bearing angle relative to X-axis, using equation (3) and (5), respectibely.

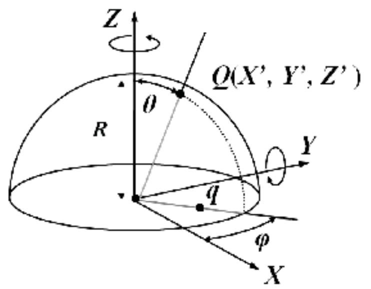
To provide the whole image whose center is identical to the vertical upward direction, all the corrected light directions must be remapped on to a pixel on the image plane. This is a straight forward computation based on the fish-eye lens projection model and sphere space whose radius is *R*. For each corrected light direction $Q[X',Y',Z']^T$, bearing angle φ relative to *X*-axis and zenithal angle are calculated as shown in equation (8) and (9). (see Fig. 8 (left))

$$\varphi = \tan^{-1}\frac{Y'}{X'} \tag{8}$$

$$\theta = \cos^{-1}\left(\frac{Z'}{R}\right) \tag{9}$$

The zenithal angle θ determines the image height r_q by quisolid projection as equation (10).

$$\frac{r_q}{R} = \sqrt{2}\sin\left(\frac{\theta}{2}\right) \tag{10}$$



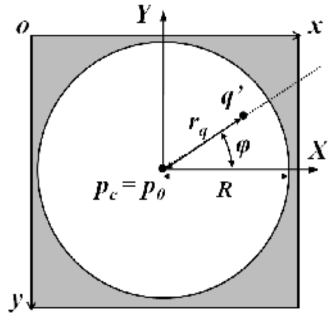


Fig. 8: Remapping the light direction in sphere space (left) onto the image plane (right).

Then the pixel position (*x*', *y*') mapped back onto the image plane is given as follows. (see also Fig.8 (right))

$$\begin{aligned} x' &= r_q\cos\varphi + x_c \\ y' &= r_q\sin\varphi + y_c \end{aligned} \tag{11}$$

3.3 Triangulation

Performing the triangulation is quite simple. The corners of the building tops are found as the corresponding target points, for example, between the pair of the fish-eye images and then the elevation angle is calculated for each camera position. As shown in Fig. 9, if the lower camera height is h_o, the higher height $h+h_o$, and the elevation angles for each camera position are θ_1, θ_2, then the target point height *H* is calculated as written:

$$H = \frac{h\sin(\pi - \theta_2)\sin\left(\frac{\pi}{2} - \theta_1\right)}{\sin(\theta_2 - \theta_1)\sin\left(\frac{\pi}{2}\right)} - h_0. \tag{12}$$

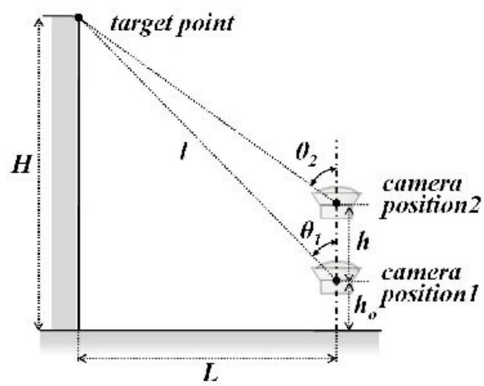


Fig. 9: Diagram for triangulation parameters definition

As a consequence, the distance L between the ground positions of camera and the target point can be calculated. Therefore, relative 3-dimensional geometry is available for examining the solar visibility on the vicinity of the camera position by single point measurement.

3.4 Shading Estimation

The proposed triangulation scheme can be applied for solar radiation examination in a straightforward manner. At the measurement point, arbitrary sun elevation T as the angle between the ground surface and the sun direction is specified by the equation shown in equation (13).

$$\sin T = \sin\psi \cdot \sin\delta + \cos\psi \cdot \cos\delta \cdot \cos\gamma \tag{13}$$

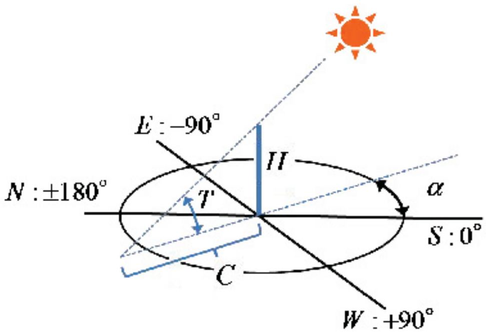


Fig. 10: Shadow length casted by a obstacle

where, ψ is the latitude of the point of interest, δ is the solar declination or the angle between equatorial plane and sun direction, and γ is hour angle which increases/decreases by 15 degrees relative to culmination each hour. The relation between a given amplitude α and the sun elevation T is described as the equation (14).

$$\tan\alpha = \frac{\cos(\psi)\cdot\cos(\delta)\cdot\sin(\gamma)}{\sin(\psi)\cdot\sin(T) - \sin(\delta)} \tag{14}$$

Hence, the shadow length C casted by the obstacle whose height H is measured by equation (12) is calculated as follows.

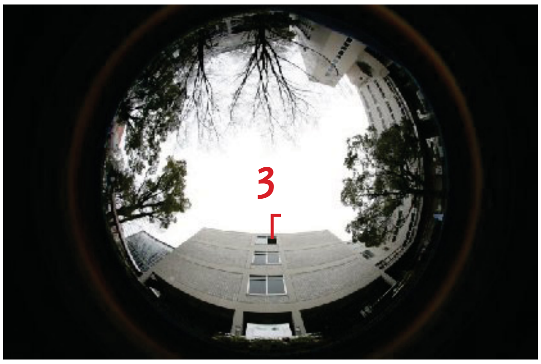
$$C = \frac{H}{\tan T} \tag{15}$$

4. Experiments

We conducted experiments to verify the proposed method. On a university campus, we took two different photo pairs with a fish-eye conversion lens (SIGMA 8mm F3.5 EX DG, see Table 1) installed onto a digital still camera (Canon EOS 5D: 4368pixel×2912pixel). The reason of the camera choice is the full-frame sensor size, which is equivalent to 35mm, so the whole circled fish-eye imagery can be captured. We settle the camera with a tripod on the ground surface. The position height differences are 0.12m (0.81m - 0.69m) and 0.76m (1.29m - 0.53m) in the two photo pairs, respectively, by changing only head position of the tripod vertically.

Fig. 11: Captured image pair #1: The camera heights are 0.69m (left) and 0.81 m (right).

The red points, #1 and #2 are the corresponding points to be targeted.



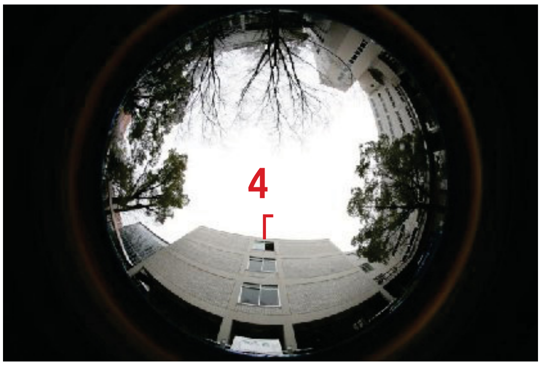


Fig. 12: Captured iamge pair #2: The camera heights are 0.53m (left) and 1.29 m (right). The red points, #3 and #4 are the corresponding points to be targeted.

Table 1: Specifications of the Fish-eye lens

Lens Construction	11 Elements in 6 Groups
Angle of View	180 deg
Number of Diaphragm Blades	6
Minimum Aperture	f22
Maximum Magnifications	1:4.6
Angle of View	180 deg
Diameter x Length	73.5 x 68.6 mm/2.9 x 2.7 in

The initial center of the image is specified by manually fitting a circle to the rounded image input, then applied the calibration mentioned above. As for the angle range of the camera view, the 90 degree view direction is associated to the radius 1353.5 [pixel] on the captured fish-eye image. The principal axis direction is corrected in each image set, from (2184.03, 970.46) to (2173.60, 1006.50) in the first image pairs, and from (2184.06, 962.91) to (2167.13, 963.58) in the second image pairs, respectively. Also the camera orientation is corrected for every image and the triangulation was conducted. The target building was 16.10 in height (measured by a laser range finder) and the proposed method gave a 3.9% and 3.5% error in height measurement as results. In accordance with the triangulation principle, the longer baseline provides higher precision. The acquired results shows that our experimental setup is capable of detecting the incoming light direction in 0.6 deg steps. At the same time, the distances to the buildings were acquired and the relative 3D positional relationship was captured. By setting up the solar trajectory, the measurement results can be used directly for computing casted shadows on the ground.

5. Conclusions and Future Works

We showed the basic functionality of the proposed vertical triangulation with proper camera calibration with simple setup. In the current implementation, we specified the targeting points on the obstacle building from the image pairs manually. So the total functionality is limited and equivalent to that of point-targeting range finder. Our next step is to take an advantage of image sensing by finding multiple corresponding points automatically using template matching process according to 2D polar coordinate image searching space, so that the height distribution make the silhouettes' edges of the obstacles that form the shadows on the area of interest. As for the measurement precision, we assumed that the fish-eye lens strictly functions as typical projection model. To achieve further accurate measurements, we may employ the fine calibration of the camera projection model to compensate the lens distortion such as in Kannala's method (Kannala, 2006). Developing a rendering scheme for graphical outputs of the visualized simulation of the solar radiation based on the insolation examination is also in our focus.

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WEB-BASED DESIGN COLLABORATION FOR DEVELOPING A MULTI-DISCIPLINARY AND INTEGRATED BIM MODEL

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ABSTRACT: *This paper presents an Internet-based design collaboration of multi-disciplinary teams for the development of a Building Information Modeling (BIM) model. The network allows geographically separated design teams to work simultaneously on a single shared BIM model, using a distributed system to achieve design integration and conflict resolution. A synchronous collaborative design platform for inter-disciplinary collaboration was developed in this study. By using the proposed platform, the members of various design teams can be connected via the Internet to work in the same virtual design space, where they can see the progress of other teams' work and cooperate in real-time. All design data is centrally maintained in a database to provide secure and systematic data management. A hybrid Client-Server and Peer-to-Peer (P2P) network model was proposed for such design collaboration. The network has two levels. Inter-disciplinary teams are linked in a Client-Server network; within intra-disciplinary members, individual team members are linked in a P2P network. This network model allows for efficient multi-disciplinary collaboration in the development of BIM models. Stable operating mechanisms and suitable access rules are imposed to maintain the integrity of the system.*

KEYWORDS: *Internet, BIM model, collaboration, multi-discipline, computer-aided design*

1. Introduction

The construction industry has the characteristics of product specialization, customization and the need for inter-disciplinary teamwork. Each construction project can be regarded as a specially designed product. Each construction project requires building its own unique model using the Computer-Aided Design (CAD) program, which is a time-consuming and labor-intensive job, and requires teamwork and collaboration. People from different disciplines build engage in inter-disciplinary collaboration through which they integrate the specialized and common design parameters from each other.

With the growing need to advance the development of the construction industry information system and to efficiently manage the construction model building, Building Information Model (BIM), a model to describe a construction model, is developed. BIM relates actual building components to the CAD model. The model therefore not only contains 2D and 3D graphics parameters, but also has the design attributes related to different fields and stages of the construction project (Eastman et al., 2008). Due to these advanced features, the development of a BIM model requires multi-disciplinary teams to cooperate on integrating their designs.

Different stages of the construction project (A/E/C, Architecture/Engineering/Construction) all require the participation and collaboration of specialists from different areas. Therefore, it is important for the team members to communicate and share the information while customizing the BIM model. Currently, however, the common BIM collaborative design model for inter-disciplinary collaboration is achieved by exchange and combination of the design files. When building the BIM model for every particular discipline, teams from different disciplines work individually at separate geographic locations and use various specialized software. Therefore, for a single construction project, there exists various BIM models from different disciplines, and all these different BIM models need to be combined into a single inter-disciplinary BIM model. Thus, the integration of BIM models is asynchronous (Chou and Hsieh, 2009). During the inter-disciplinary collaboration process, numerous design parameters need to be set. Although some of the parameters can be designed by an individual team based on their specialty, most of the parameters need to be discussed and determined by more than one team. This therefore requires several rounds of inter-disciplinary communication and coordination to achieve such integration. When combining the individual BIM models into a single BIM model on relevant software platforms, the design parameters of different disciplines are likely to conflict with each other. Due to dependency between a number of design parameters and the lack of information on each team's design progress and details, resolving the conflicting parameters consumes a large amount of time and human resources. This makes the integration of the designs from different disciplines difficult.

In recent years, with the continuous development of Internet-related technology and the increase of network bandwidth, the distributed network system now can economically provide support to long-distance real-time operations. This revolutionarily transforms the modes of organizational communication, resource exchange and corporate collaboration. With the rapid growth of network and computer-based technology, some researchers have utilized web-related technologies in CAD to allow real-time synchronous collaboration between users over the web (You et al., 2007). All these systems have successfully shown that geographically distributed users can share data and work together to build and edit visualized models over the Internet.

With regards to the above-mentioned problem in integrating the individual BIM models from different disciplines since the Internet is an ideal medium to support distributed teamwork for communication and exchange of design data, the combination of individual BIM models with the database can allow the efficient integration and management of the inter-disciplinary design data. It also enables the information to be made available for future operations.

The goal of this study is to leverage on Internet technology to create a collaborative design environment which allows all connected teams to work together in the same virtual space, integrating their discipline-specific designs into a single BIM model. In this environment, each online user can add their individual contributions to the model, and also view the progress of one another's work in real-time.

The process of multi-disciplinary collaboration in construction projects is shown in figure 1. Usually, only one team works on the design at a time and each team has a group of members to share the work and cooperate concurrently. When one team completes their design, the design is then transferred to the next team for further design work. If any change in design is required, the design will be returned to the previous team for adjustment. In such a complicated construction design and development procedure, the specialist of each discipline is unable to accomplish the project design by himself. It requires the collaboration of the teams from different disciplines to obtain the optimal solution with thorough consideration from every aspect. To achieve this target, the teams of different disciplines will form an inter-disciplinary collaboration relationship with one another. The BIM model design follows the process of initial design, submission, verification and confirmation. At any point in time, the project design information is usually under the purview of a particular disciplinary team, and the members of each team cooperate simultaneously.

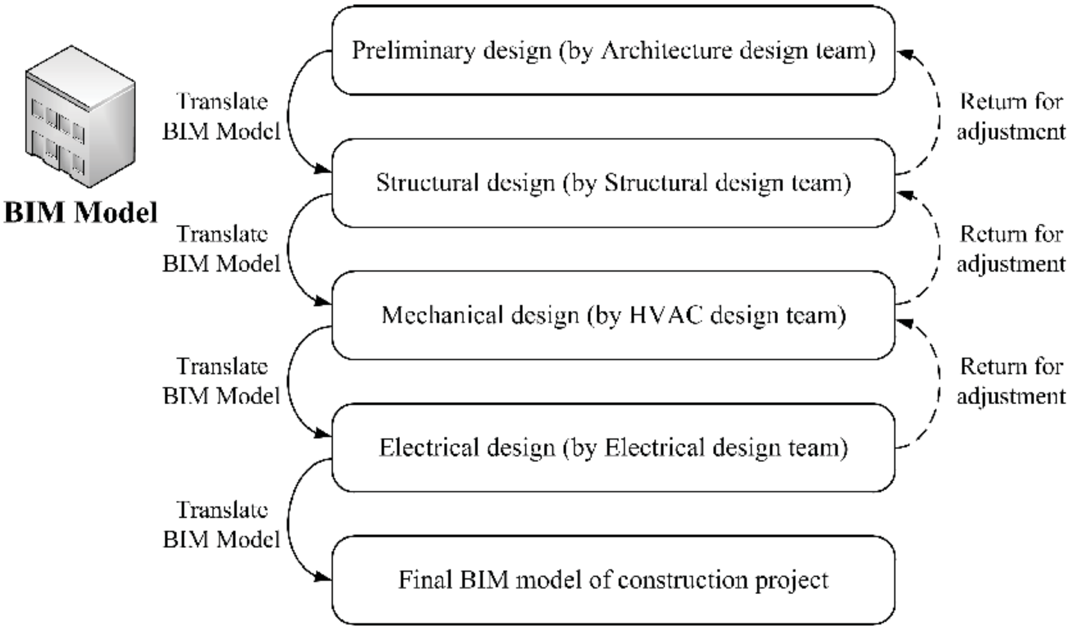

Fig. 1: Construction Project - BIM Model Building Process.

Therefore, the proposed Internet-based mode and technology must support this design process. It should not simply allow the BIM model to be transferred among teams online, but also allow the members of each team to cooperate concurrently in an Internet-connected environment. For such a distributed system, a network model would be a basic requirement. There are two major types of communication network models, one is the Client-Server network, and the other is the Peer-to-Peer (P2P) network. The Client-Server network is the most basic connection model to connect the global server with each client. In this model，the server is acting as the bridge for data transmission between each client. On the other hand, the main feature of the P2P model is that it consists of the peers acting as both the server and the client. Therefore, all the peers have the capability to communicate with each other directly. The advantages of the Client-Server network model are that they are more secure and information is managed more easily, not requiring unnecessary duplication of information, whereas the advantages of the P2P network model are that they enable more efficient communication, are more crash-proof, and take advantage of idle computing capacity. In this environment, each online user can not only add their contribution to the model in sequence, but also view the progress of others' work in real-time.

The BIM model has two types of collaborations, which are inter-disciplinary collaboration (e.g. the collaboration among the structural engineers, architects and construction engineers) and intra-disciplinary collaboration (e.g. the collaboration among the architects participating in the same construction project). The inter-disciplinary collaboration is asynchronous. Apart from the primary discussion about the design plan at the initial stage, the collaboration model is that each team will not pass on its design to other teams until all the designs or modifications from its responsibilities are completed. Therefore, achieving effective exchange among the teams and maintaining the consistency of information becomes the main aim of the collaboration. The Client-Server network structure provides a global database and enables each team to exchange and manage the data via the Internet. This is considered to be the optimal model, when considering data maintenance and management efforts. The intra-disciplinary collaboration is synchronous. The common collaboration model is to assign the design tasks to the various team members and work simultaneously. During the collaboration, the team members need to communicate frequently to view the progress as a whole. This process enables the integration of designs from various members. Hence, the main aim of the collaboration is to maintain the information transmission efficiency, the average workload of the distributed process, the system fault-tolerance level and convenience in connecting each member. Considering the stability, autonomy, extensibility and convenience of the system, the optimal choice is the P2P model. The traditional Client-Server network and the emerging P2P model can support both of the above-mentioned collaboration models. This study focuses on the characteristics and operational model of the construction project's inter-disciplinary and intra-disciplinary collaboration, and proposes a hybrid Client-Server and P2P network model.

2. Objective

Considering the inter-disciplinary design attributes and parameters in the BIM model, and the collaborative operation model, the objective of this paper is to study the hybrid Client-Server and P2P network model. The current unitary network infrastructure can only satisfy the need of a single type of construction project collaboration. A hybrid network infrastructure can better meet the requirements of the inter-disciplinary collaboration of a construction project and provide effective communication modes between members from different disciplines. In this way, real-time collaboration of inter-disciplinary and intra-disciplinary teams can be achieved, and the efficiency of the BIM model collaboration, improved. The network model is illustrated in figure 2. Firstly, every team needs a local server that represents the team. These local servers should be on-line all the time and connected to a global server that is responsible for the inter-disciplinary collaboration, in the Client-Server mode. The global server manages a unique BIM model with different versions, and updates the data in the local servers instantly. On the other hand, users in each disciplinary team can use their own peer PC to communicate with each other following the P2P network model, and connect to the local server of their team directly or indirectly. Their online status will not affect the operation of other peers or the local server. However, in the client-server network, only one team works on BIM model at any one time and the members of the working team collaborate synchronously in a P2P network.

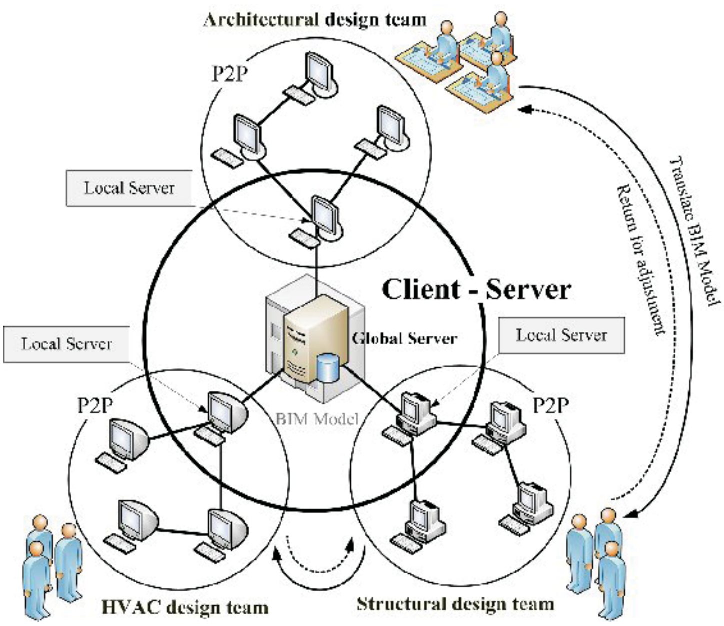

Fig. 2: Hybrid Client-Server and P2P Network Model based Inter-discipline Collaboration Platform.

This study uses the network collaboration method to solve the problems faced by stand-alone CAD systems, and proposes to set up the unified BIM model to achieve the inter-disciplinary collaboration. Based on the integration requirements, this paper proposes to set up the BIM design system to integrate the data among each discipline. The teams of each discipline can work on this virtual platform to assign jobs, cooperate and coordinate with one another to build a final construction model, which reflects the integrated design. Any inconsistencies of the design parameters can be monitored by the system and displayed on the BIM model. It can then be eliminated by further coordination. The teams from different disciplines and the team members from the same discipline can work on the same platform and build a unitary BIM model. This collaborative design process is the same as executing the construction virtually. Since all the design conflicts have been detected and eliminated through the virtual construction process, the actual construction will simply be to realize the BIM model. This can solve the problem faced with a BIM model having being designed by an asynchronous-collaboration inter-disciplinary team. Besides, the inter-disciplinary teams can cooperate and communicate with one another on the system platform to build the inter-disciplinary BIM model, and to integrate and synchronize the design parameters from different disciplines.

This study also proposes the concept of a sub-model. It extends the normal two-tier BIM model (e.g. building components and the entire BIM model) into a three-tier model (e.g. building components, sub-models and the entire BIM model). This increases the convenience of the BIM model data transmission and integration, and improves the efficiency of collaboration between the inter-disciplinary teams. Furthermore, this study proposes the hybrid Client-Server and P2P network model, which focuses on all the participants in the entire design process. Moreover, the study is based on the analysis of the job assignment and collaboration between each participant. It establishes the network operation model for different participants to collaborate and the method to eliminate conflicts among the inter-disciplinary teams, enabling the inter-disciplinary teams and intra-disciplinary members to coordinate and integrate the design parameters on the shared platform. This leads to the development of an optimal integrated and unified BIM model.

3. System Requirements

In this study, the relevant functions and architecture plan of a system platform for inter-disciplinary design collaboration for BIM model development were proposed for developing a prototype system. Starting from the system development perspective for fulfilling the functional requirements, some operational mechanisms of the system were proposed as the basis of implementation.

3.1 Sub-model

The BIM model for construction projects usually consists of some basic building components such as columns, beams, walls and boards; it has a two-tier architecture. In order to improve the efficiency of the construction process and increase the data transfer speed, we introduce a tier of sub-models between the components and the BIM model was proposed. Therefore, the BIM model in this study has a three-tier architecture. The first tier includes the components. The second tier has the sub-models, which are the building units made up of components from the first tier. The third tier is the entire BIM model composed of the collection of all sub-models. In the network-based inter-disciplinary design collaboration process of construction projects, the inter-disciplinary teams will frequently exchange the BIM model. However, the BIM model records massive volumes of multi-disciplinary design information and is very large. If the entire model is transferred on the network, the large amount of data will incur a heavy burden on the network transmission and slow down the data synchronization. Moreover, when a multi-disciplinary team develops designs for construction projects, they would spend much time on the design of a specific building unit in the model. Therefore, the proposed sub-model tier would divide the BIM model into sub-models, so that the data exchanged during the BIM model design process can be reduced. In addition, one team does not need to wait for another team to complete their designs before they deliver their work. If the predecessor team has already completed some of the sub-models, they will be able to deliver these sub-models to the successor team, so the efficiency of network-based inter-disciplinary collaboration can be greatly improved. The proposed a three-tier architecture of BIM model is shown in figure 3.

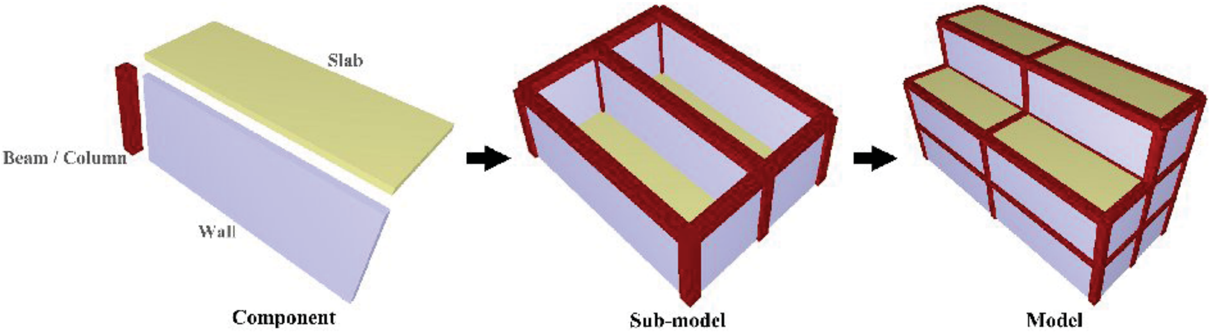

Fig. 3: The proposed a three-tier architecture of the BIM model.

3.2 Online/offline mechanism

In the Client-Server network model for inter-disciplinary teams, building the BIM model requires teams from multiple disciplines. The local server of each team must first login to the global server using the team-specific account and password. The team can then be identified and the relevant data of the BIM model design transferred from the global server. The global server can also manage the permissions for modifying existing sub-models of the BIM model, in order to ensure the uniqueness of the sub-models and consistency among the BIM model in different teams. In the P2P network model for intra-disciplinary members, each team has a local server that is the root node connecting peers in the team. The connections between peers form the P2P network model. In this model, every peer can join or leave the team at any time. If one peer wants to join the team online to participate in the design task, the system can use IP broadcasting to search and provide a list of nodes that have enabled server mode from the online team members, other than directly inputting the IP address and port number to assign the target. The peer can then select which one of them to connect to. This feature simplifies the process of connecting to other peers.

3.3 Data synchronization

In the data management aspect, inter-disciplinary team collaboration mainly consists of inter-team and intra-team parts. For the inter-team part, the Client-Server network architecture is used. The global server provides all teams with a data exchange and management center accessible through Internet, which manages the BIM model data generated by every team. The P2P network model is used for intra-team peers. The design data is stored and communicated in the same format, which is a string started by a keyword specifying its type and followed by its individual attributes. For recognition and processing of data in a distributed environment, a common protocol among peers is established by a system rule which reserves a keyword and specifies a set of attributes for each type of data. On the other hand, each datum must have a unique ID to be distinguished in the distributed environment. In the aspect of data consistency, the permission on each model component can only be granted to one team at a time. The other teams cannot edit the component or modify its related attributes and multi-disciplinary parameters, which ensures the consistency of the model objects among all the teams. The proposed data synchronization in intra-discipline is shown in figure 4(a). In the inter-disciplinary teams, when the team holding the permission updates the BIM model, their local server will upload the new BIM model to the global server, so that other teams' local servers can retrieve the updated BIM model instantly. The local server in a team can centralize and manage the design data and push it to every peer in order to facilitate discussion among the team members. For data exchange among team members, each peer has to notify all the other peers by broadcasting its modification, such as addition, deleting, scaling, or moving a modeling object, to the model immediately after an action is completed and confirmed. This is required in order to achieve data synchronization for every user to have consistent views of the shared model, which is continually being updated by all users in real-time. The proposed data synchronization in inter-discipline is shown in figure 4(b).

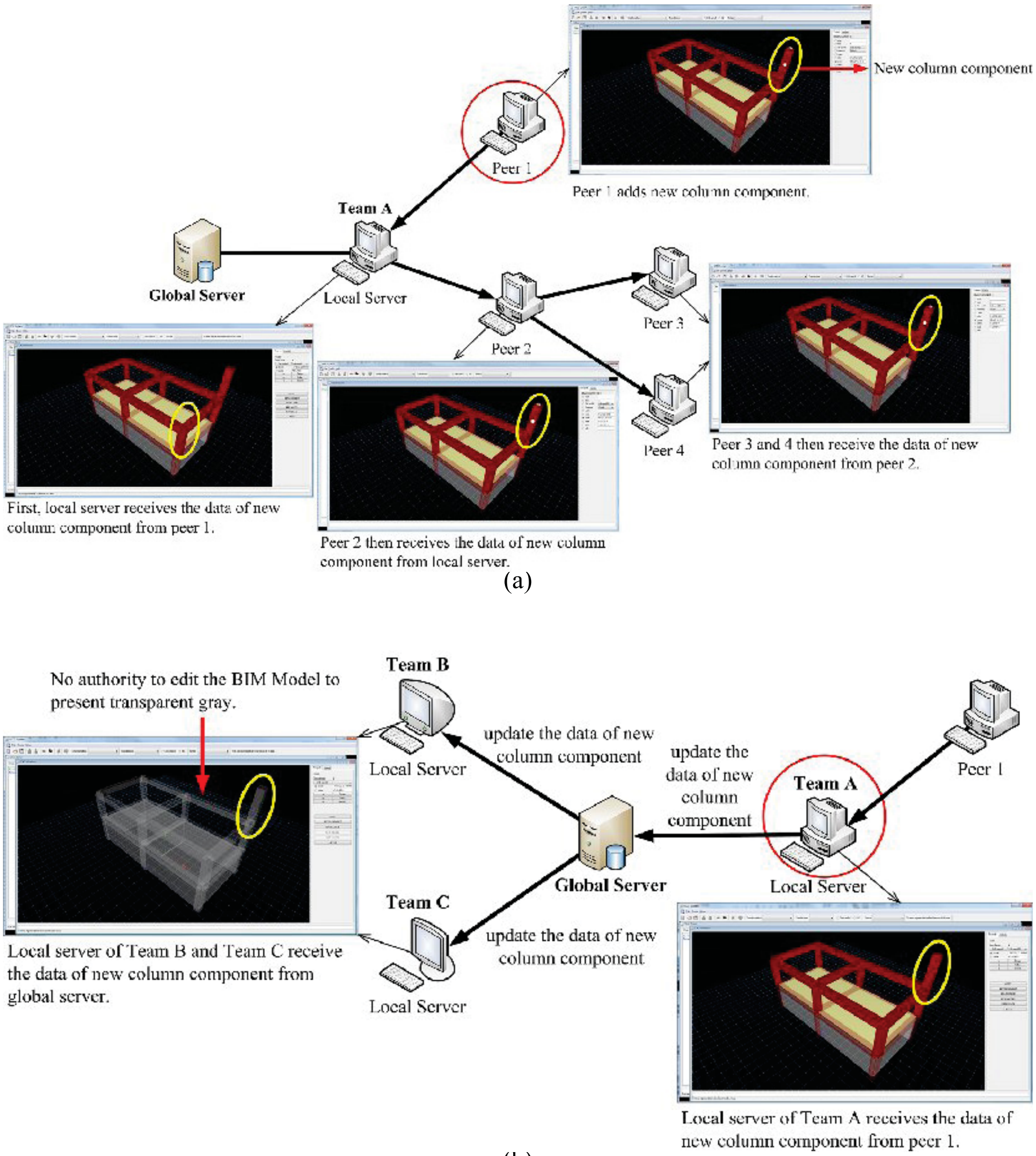

Fig. 4: Data synchronization of the proposed system.

3.4 Access management

In the inter-disciplinary real-time online collaboration setting, due to the requirement of data consistency, multiple teams or users editing the same model object should be avoided. Therefore, rules on permissions for model objects are required. The model object permission management consists of two parts, namely the inter-disciplinary and inter-team management, and the intra-team user management. For the inter-disciplinary team, the permissions of the sub-models in BIM model are managed and controlled by the global server. The permission for a sub-model in the BIM model can only be possessed by a single team. Only the members of that team can edit and modify the sub-model and its components. Other teams without the permission cannot edit or modify the sub-model, and can only view it. The proposed access management in the inter-disciplinary team is shown in figure 5(a). Among the intra-team users, the permission management of the model objects relies on the lock-based mechanism. To ensure that a lock on an object will not

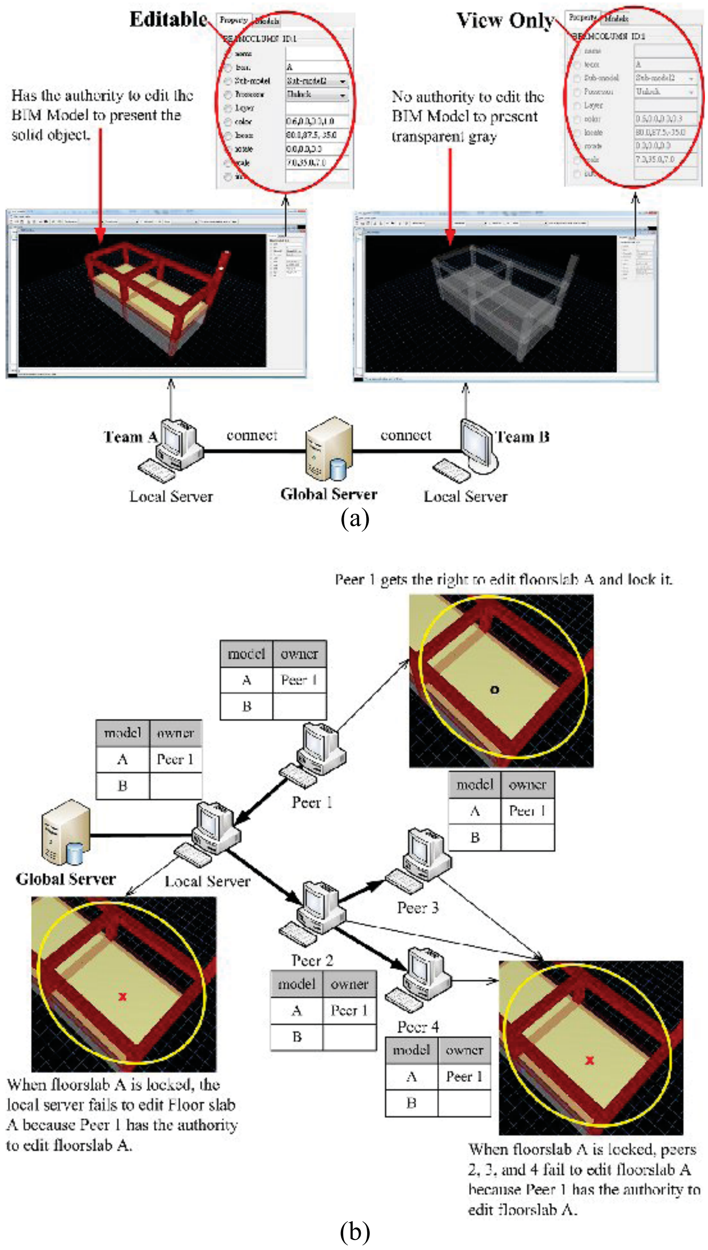

Fig. 5: Access management of the proposed system.

be granted to more than one user at any one time, a locked object cannot be requested until its owner releases its lock. To ensure all the locked objects belong to an owner, a peer automatically releases all its locks on objects immediately before leaving the group. The proposed lock-based mechanism is shown in figure 5(b).

3.5 Data transmission and communication protocols

In both the inter-disciplinary and intra-disciplinary online collaboration environments, inter-team or intra-team exchange of BIM model data is very frequent. The global server, local servers and peers in the teams will receive and process data from different sources at the same time. Therefore, the proposed system in this study employs multithread processing for data from different sources. The global server, local servers and peers can receive data from different sources simultaneously and process them accordingly. Different threads will not interfere with each other. The multi-thread capability included in Java can be used to fulfill this goal by creating multiple threads to run concurrently, and each thread has a connection to another peer. For the inter-disciplinary teams, the data transmission of model objects is managed by the global server. Each disciplinary team has a local server that is always online and in charge of sending real-time model data to the global server and receiving updated model data from it. In the intra-disciplinary team, each peer connects to other peers using the Application Level Multicast (ALM) technique in the P2P network. In the ALM, data is transmitted through the tree-structure overlay network composed of unicasts between nodes in a multicast group, so that the transmission efficiency is improved. The proposed data transmission mechanism is shown in figure 6.

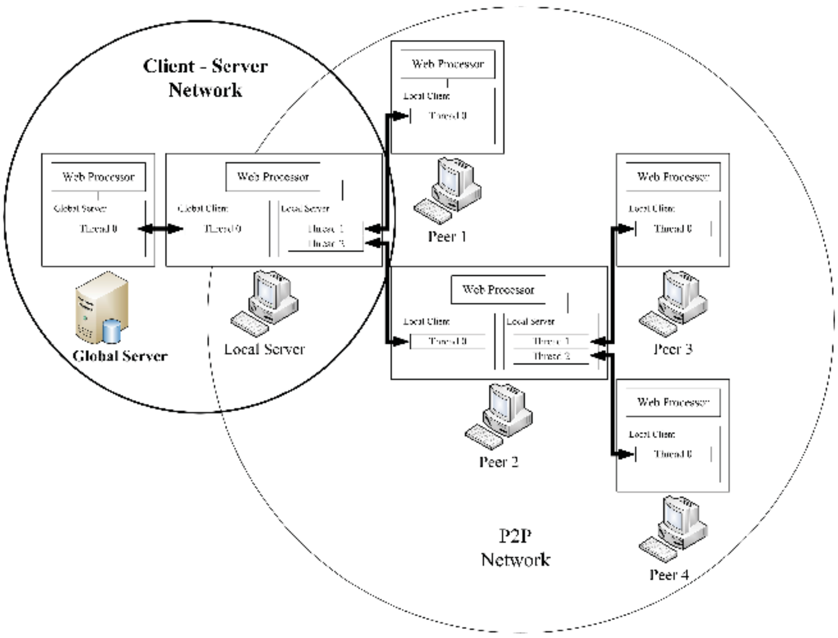

Fig. 6: Data transmission mechanism of the proposed system.

3.6 Version management

The BIM model version management function and mechanism proposed in this study can effectively manage BIM design data generated in the inter-disciplinary team collaboration, and enhance the efficiency of inter-disciplinary teams' communication, and data recoverability. When each disciplinary team finishes their design and delivers it to the successor team, the global server will automatically keep a record of the delivered sub-model. Therefore, there will be several backups of multi-disciplinary sub-models belonging to different design stages, which can be used to rollback the sub-models later if required. During the design process, when the team in charge at the current stage modifies the sub-model such that it conflicts with the parameters or data designed by previous team, they can choose any of the backups left by the previous team in the global server to roll back to. This feature facilitates the coordination and communication between inter-disciplinary teams in dealing with conflicts in design parameters or data, and improves the efficiency of design collaboration.

3.7 Network connection

In the hybrid architecture of Client-Server model and P2P model, the global server will connect to each local server at a certain point of time and update the data in the local server to the most recent version. The local servers will also upload the BIM model data to the global server at a fixed time. Subsequently, the global server will broadcast the BIM model data to other local servers. Therefore each team must have a local server that is always online to perform the communication functions with the global server, and receiving and sending of model data. If the local server of the team currently in charge suddenly goes down, there should be other peers available in the team and one of peers promptly becomes it. The proposed connection recovery mechanism in Client-Server model is shown in figure 7(a). When a peer leaves the design group, other peers must not be affected by its departure. When one peer leaves the group, any linked peer must connect to other nodes to remain part of the group. First, they will attempt to connect to the peer to which the leaving peer is connected. If there is no such peer, then the leaving peer is the root. In this case, the peer that placed first in the shared list of group members becomes the new root of the group, and the other peers connect to it to maintain their connection to the group. The proposed connection recovery mechanism in P2P model is shown in figure 7(b).

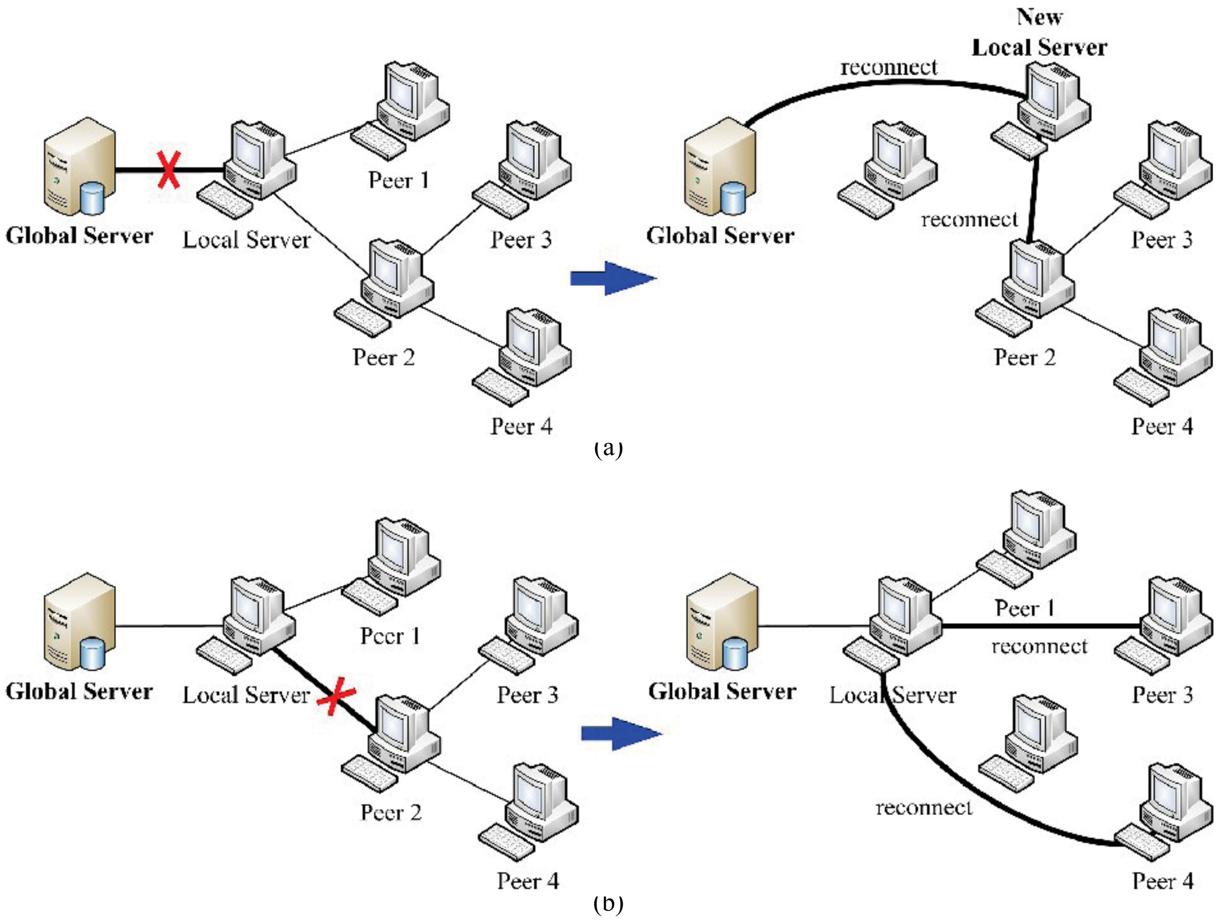

Fig. 7: Connection recovery mechanism of the proposed system.

4. System Implementation

The proposed system can be thought of as a fusion of a CAD program, a communications program, and Web connection program. The proposed system architecture is a four-tier system, as shown on Figure 8. The first tier is the LoginWebCADSystem for identification of team login; the second tier is the WebCadSystem, which can switch the interface style of the system; the third tier, CadSystem, is in charge of the entire system's input and output, as well as the network access permission; the fourth tier includes the CadFrame module responsible for 3D visualization, the CommunicateFrame module for video conference, and the WebSystem module for network connection and data transfer. The CadFrame contains the CADJPanel object and various sub-model and component objects, which are the core of the 3D graphics system environment. They control the input and output of all 3D models as well as the permissions on every model and component that can be used by the team members.

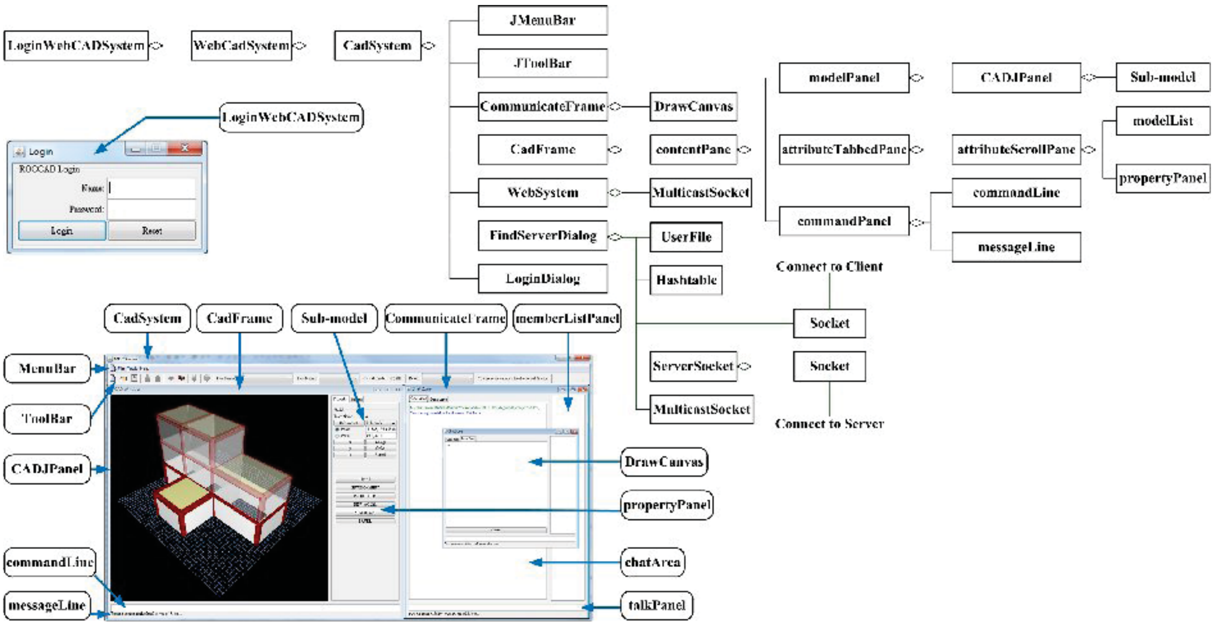

Fig. 8: The object model of the proposed prototype system.

5. Conclusions

This paper proposes a hybrid network which allows for coordination of interdisciplinary teams in BIM. This network allows designers and engineers to stay in real time communication, and to transmit the attributes of model objects and model parameters. Network technologies maintain information consistency and govern access throughout the network. Designers and engineers are thus able to coordinate their development of the model and objects based on the design objectives. This network represents an improvement on traditional face-to-face meetings and discussions collaboration, and will help to improve overall project efficiency.

6. Acknowledgement

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ForBAU – MODEL-BASED MANAGEMENT OF INFRASTRUCTURE PROJECTS

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ABSTRACT: *The declared aim of the "Virtual building site – ForBAU" research project was to create a digital site model from the planning to the execution phase through to the LifeCycle perspective. The purpose of ForBAU was not only the three dimensional modeling of the structure, but also of the ground and the terrain. To enable the planning of a complete model, the mentioned submodels must be brought together. The challenge was that the individual models are created with different, highly specialized applications. Against this backdrop, interfaces and tools have been designed for the specific purpose of linking diverse tried-and-tested insular software solutions to form a single, comprehensive model. This model can be used to easily transfer changes in route planning to the geometry of infrastructure buildings such as bridges. Furthermore the holistic model is used for the sequence planning in the infrastructure construction. Here the planning of earthwork processes is a major challenge. ForBAU worked out a solution with which the planning of earthwork can be improved by applying the Discrete Event Simulation. To improve the supply of materials in the execution stage a new logistics concept has been developed. The aim was to deliver materials to the place where they will be installed. As a result, transport, search and storage times can be reduced. In order to depict the progress made on the building site in the digital site model at any given time, RFID technology is employed to automatically collect, track and record the building components and operating materials.*

KEYWORDS: *digital construction site, ForBAU, parametric 3D modeling*

1. Status quo

In the present day and age, the construction industry is beset by major challenges. Ever more complex building projects need to be accomplished within increasingly tight deadlines. At the same time, due to the keen competition in this sector, prices are being forced down significantly. The German construction industry will only be able to meet these requirements if it succeeds in increasing its efficiency during the planning and execution stages. It would appear, however, that the current processing standards achieved by building contractors lag far behind those attained by other industrial sectors, particularly from the point of view of adhering to time schedules and cost stability.

There are numerous reasons for this: the difficult circumstances that prevail in the building industry in general, including the construction of unique "one-off" structures, dependence on weather conditions, the pronounced fragmentation of the sector and the high level of segmentation along the process chain. At the same time, only very limited use seems to be made of state-of-the-art information and communication technology compared with other sectors of the industry. Although mature software products are employed for specific partial assignments, there is still plenty of room for improvement in terms of both efficiency and quality, particularly with regard to enhancing data flow and putting existing digital data to further usage.

The resolute use of digital technologies throughout can achieve greater workflow transparency by reducing interfaces and optimizing the cooperation between the different parties involved in the projects. This potential is employed in many sectors, such as the automotive industry, shipbuilding or general plant construction. Until now, however, these concepts have only been put to restricted use in the building sector.

Recognizing that action was called for, the "Virtual construction site – digital tools for construction planning and execution" (ForBAU) was set up in January 2008 with the aim of depicting a complex building project holistically by means of a single digital building site model. This simulated building site is employed as a central planning tool during all phases of the relevant project. An interdisciplinary team consisting of members of seven departments of Technische Universität München, the University of Erlangen-Nuremberg, Regensburg University of Applied Sciences and the German Aerospace Centre (DLR) joined forces to realize this vision along with more than 30 industrial partners including building contractors, firms of planners and engineers, construction equipment manufacturers and IT partners for digital tools. The interdisciplinary alliance was sponsored by the Bavarian Research Foundation from January 2008 to December 2010.

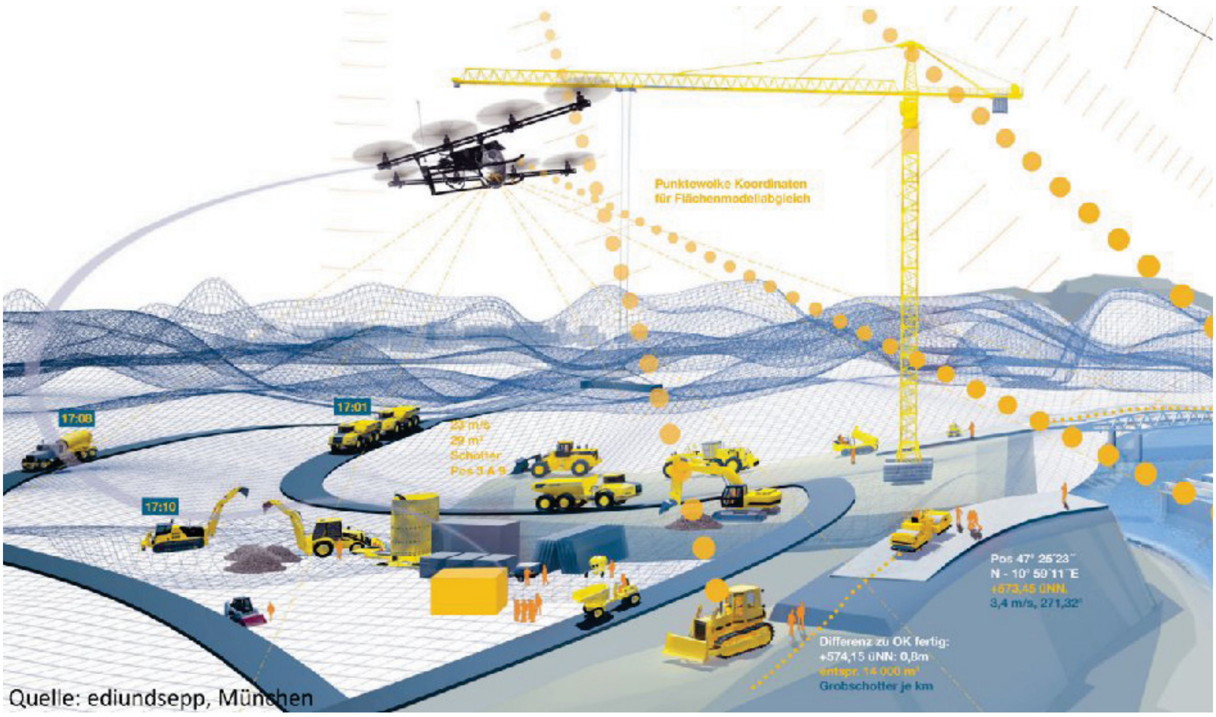

Fig. 1: The vision of a digital building site

2. New technologies for construction planning

The digital construction site is a virtual simulation of the real site. It contains valuable 3D planning data, making it possible to plan the construction sequences more carefully to begin with, then to test them on the model and subsequently to monitor the actual building process. The digital building site comprises various partial aspects which are described below in greater detail.

2.1 3D modeling

The ForBAU research alliance started out by observing the planning processes. The three-dimensional modeling helps to detect faults, such as building components colliding, before the plan has even left the building contractor's desk, thus keeping costly corrections on the building site to a minimum. Apart from three-dimensional models (see Figure 2), state-of-the-art CAD programs also support fully parametric ones. This means that adjustments – modifying the spacing of supports, for instance – can be implemented very quickly by changing one of the parameters. The aim of ForBAU is not just to simulate the building construction, however, but also to create a geological model of the subsoil and the terrain, to depict the construction site installations and finally to blend the various models together to form a single site information model – the digital construction site.

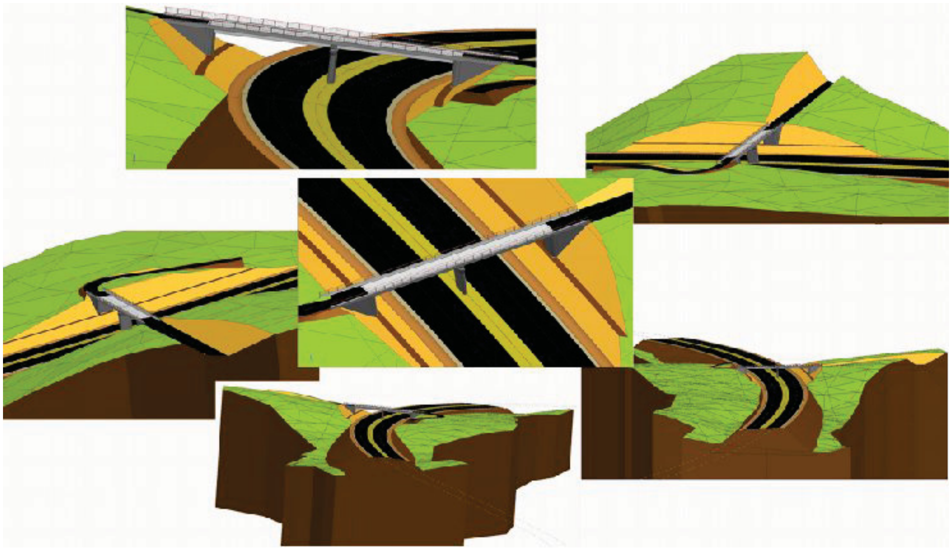

Fig. 1: Parametric 3D model of a construction site (Günthner and Borrmann, 2011)

2.2 Integrating submodels in the digital building site

The submodels depicted in Figure 3 need to be merged together to enable plans to be drawn up on the basis of a holistic model. The challenge is that the individual models are created using different, highly specialized applications, as is often the case in the construction industry. For this reason, part of the ForBAU project was devoted to developing special software known as an *integrator.*

One of the *integrator's* key purposes is to couple the drafted route, which is achieved with the help of established 2D drafting tools, with bridge models that are generated using parametric 3D modeling. By coupling these aspects it is possible to transfer any changes in the layout of the track, which frequently occur even at a later planning stage, to the bridge models, enabling the geometry of the bridges to be automatically aligned to the new route.

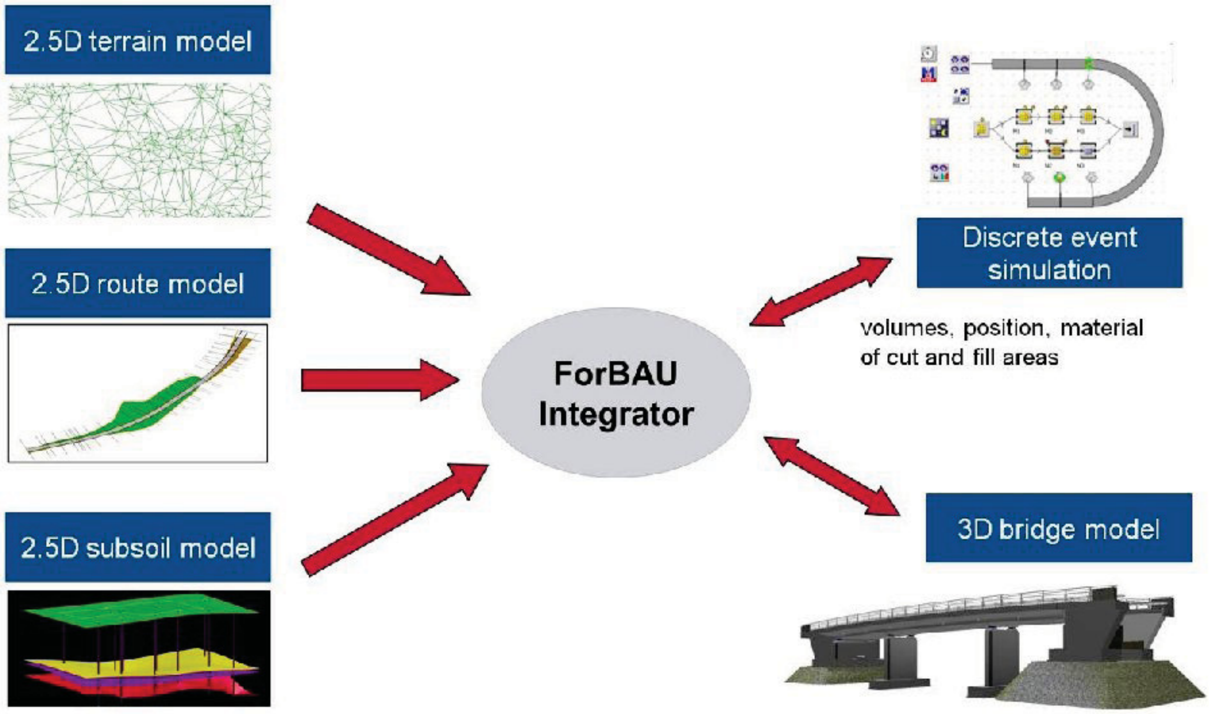

Fig. 2: The ForBAU integrator linking various submodels of the digital construction site together (Günthner and Borrmann, 2011)

This coupling process is implemented by importing the main track parameters (line of axis, gradients, cross-sections) with the help of the standardized LandXML format. The ForBAU integrator uses this information to create a 3D model of the proposed route. Another feature that is derived from the LandXML format is the digital terrain model (DGM), which maps the relief of the ground surface. The integrator is also able to import terrain models.

All this information on the proposed route and the surrounding area can then be transferred to the CAD system *Siemens NX* which was specifically selected for the ForBAU project by way of a tool for the parametric modeling of bridge structures. We begin by creating three 3D reference lines designed to describe the designated route for the track. They serve as geometric reference points on which the geometry of the components of the bridge model is based via parametric dependencies (Figure 4).

In the event that the course is changed in the route planning tool at some later date, the *integrator* is able to identify the relevant modifications and update the reference line.

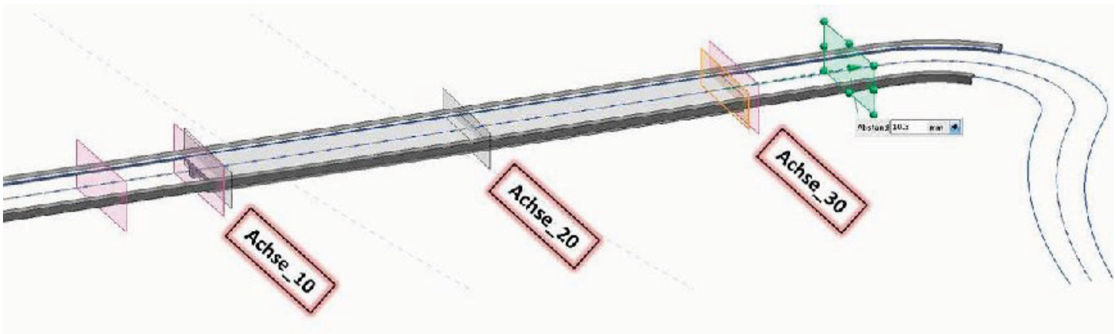

Fig. 3: Reference lines of the proposed route and the corresponding bridge geometry Günthner and Borrmann, 2011)

Another key purpose of the ForBAU integrator is to calculate the volume of earth to be extracted or filled in. In order to generate this information, the integrator has to incorporate the 3D models of the subsoil and the terrain into the 3D model of the proposed route.

2.3 Building process workflow simulation

Operations scheduling in civil engineering is no easy task. Conventional methods of assessing the timeline for earthworks are currently confined to a number of individual pieces of equipment, whilst the mutual impact of several different operations can only be assessed through experience or by estimating possible influential factors. ForBAU has devised a solution for improving civil engineering operation schedules based on simulation technology. In this way, it is possible to optimize the use of resources by conducting numerous experiments during the simulation phase and analyzing the results. This involves using different plant combinations and alternative site facilities as variation parameters. Several track options can be taken into consideration and compared from the point of view of different material resources.

Another problematic aspect at big construction sites is finding the most economical cut and fill solution for a certain volume of earth. Until now, this was usually tackled by trying to reduce the average haulage distance between the extraction point and the dumping area. Transport costs not only depend on the distance, however, but also on the nature of the terrain, the vehicles employed and other general site conditions.

Against this background, ForBAU set about devising a way of saving on costs for various transport combinations using a workflow simulation. This can be followed up by a mathematical optimization process to ascertain how much earth needs to be dug out at which point and deposited at which dam in order to keep the total transportation costs per cubic meter to a minimum, thus reducing the number of trucks and the overall financial outlay. In addition, it is also possible to examine the feasibility of constructing a site road and to determine which haulage equipment is best suited for the scenario with or without a site road.

Importing the 3D model of the construction site into the simulation environment also provides a 4D visualization option which shows up any spatial and process-related collisions. The advantage of using simulation is that the detailed plans can be backed up by all the experiments to support discussions with everyone involved.

It also allows the simulation model to be continually updated during the construction stage as well as supporting a target/performance analysis of progress made with the building operations. In the event that delays nevertheless occur during the execution phase, due to unfavorable weather conditions etc., the ForBAU approach allows a flexible response by adapting the resources to the new situation in the simulation.

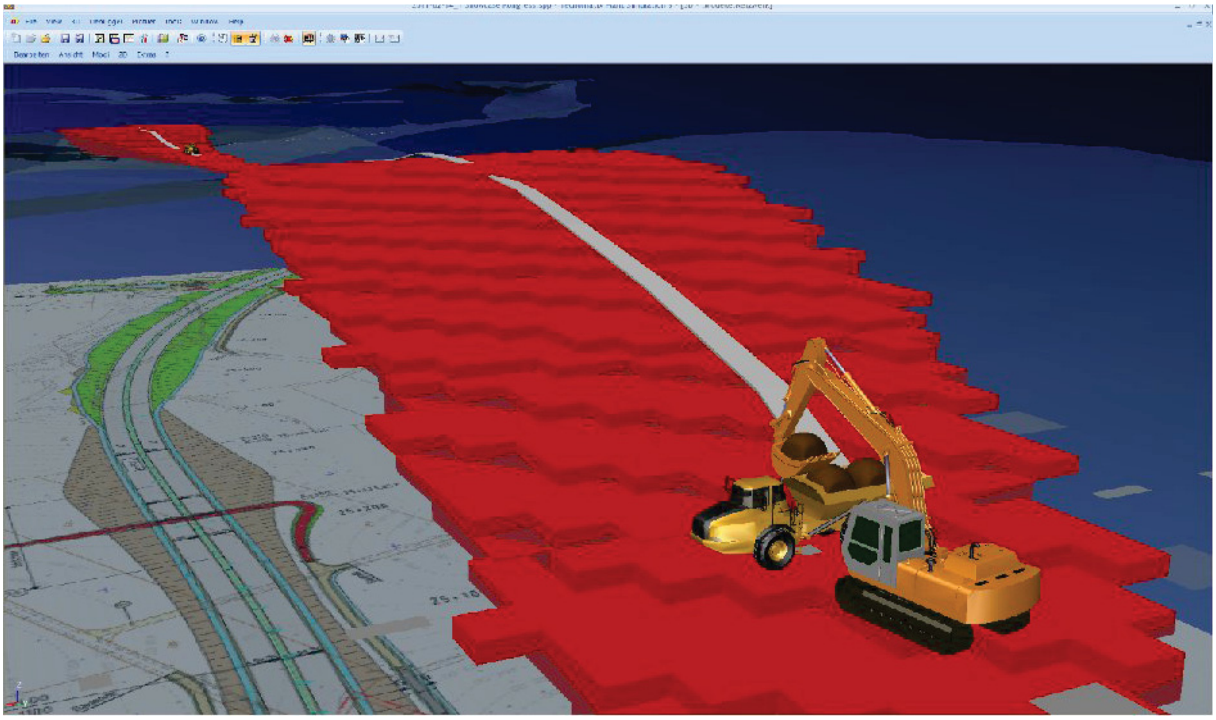

Fig. 4: Simulation of earthwork processes

3. Monitoring and control of the construction work

The benefits of good planning only become evident in the execution phase, as this accounts for the bulk of the construction costs. For the time being, however, the use of high-quality planning information suffers considerably from the lack of efficient means of comparing it with actual circumstances on the building site without delay.

Changes of plan are inadequately documented or not recorded at all. Information on current progress or delays in operations reaches the person responsible too late so it is impossible to respond quickly. In order to exploit the potential of the digital building site, it is therefore necessary to couple the virtual planning with the actual execution process. Information about the construction process needs to be relayed to the digital site information model in real time if changes in circumstances are to be documented promptly.

Process data means all the information that serves to record the progress made in the building project or describes the material and information flows. Nowadays it is typically collected on the building site in the form of written or digital documents (delivery notes, daily reports). These process data are often stored in a decentralized place, such as the foreman's or the construction supervisor's laptop, and there is usually some delay in forwarding it to the central IT system or the information is incomplete. It is only possible to control the construction operations efficiently and proactively, however, with the help of up-to-date information. So one of the goals has to be to simplify and speed up the recording and forwarding of the process data to a central IT system using appropriate technology and standardized interfaces.

3.1 Real-time data mining based on radio-frequency identification (RFID)

Process data are required for monitoring and controlling a building site - preferably in real time. Identification technology is employed to enable these data to be collected quickly and reliably during operations. One very promising type of identification technology is RFID technology. RFID stands for radio-frequency identification and refers to a technology designed to read and enter information without any eye contact with the help of electromagnetic transmission.

A study on the topic of construction logistics (Günthner and Zimmermann, 2008) was conducted among contractors and planning firms at TU München in 2008. Among other issues, this study investigated the potential serviceability of RFID for the building industry. These companies anticipated the greatest benefits from improving the relevance of inventories by recording supplies without delay, prompt goods inwards and goods exit inspections and minimal administrative work by reducing manual operations. The filling out of consignment notes and the attendant incorrect documentation is one pertinent example. Other promising aspects that have been identified are the prompt project evaluation and utilization of a detailed database for later projects and a reduction in the incidence of missing parts.

It is estimated that this would cut administrative work by almost 14% and replace about 8% of the overall construction time with automatic data acquisition. Financial savings of up to 11% could be achieved through the organization, coordination and expedient reconciliation of operations, about 7% through the punctual delivery of consignments and another roughly 5% on storage facilities at the building site and the contractor's yard respectively. The results of the study will serve as a basis for various interesting scenarios for the industry and are to be developed and tested from the point of view of the labeling solutions given below.

3.2 Transparent material and process monitoring on building sites

Until now, most of the processes and the material flows on the building site could only be documented with the help of manual records such as daily logs and delivery notes etc. The new identification solutions based on RFID suggest numerous applications that might introduce more transparency into the operating procedures on the building site.

3.2.1 Labeling of drill pipes in special earthwork projects

In collaboration with Bauer AG, a labeling concept for special civil engineering pipes was devised. The aim was to document the lifespan of the individual drill pipe components. The number of drill pipe components supplied to the building site usually includes a few spares to be on the safe side. It may happen that certain drilling components are never used whereas others are needed for each drilling process, for instance, so different parts are subject to varying degrees of wear and tear. Documenting the operating hours provides new possibilities for drawing up maintenance schedules, which can be compiled from the long-term information on the database irrespective of the usage, work-load and soil conditions. As every side of a pipe component represents a functional surface that is subject to a great deal of wear and tear, they cannot simply be labeled using a RFID transponder, so it is impossible to document the operating hours in this way. The RFID drill-pipe screw was developed to solve this problem.

Fig. 5: RFID drill-pipe screw

The diameter of a drill pipe can measure anything up to four meters and they are joined and held together with the help of couplings. For safety purposes, the coupling sleeves are usually oversized, so it makes sense to replace drill-pipe screws with tight-fitting, plastic screws containing an integrated RFID transponder. This is read and recorded by the aerial on the mast during operation after it has been installed.

3.2.2 Labeling of shuttering components

Labeling formwork components not only helps to keep a careful track of these components in the contractor's yard and on the building site but also facilitates recording the hire period of each individual item and settling accounts. Other benefits include avoiding confusion, tracing damage back to the perpetrator and determining operating times for the relevant components, which in turn makes it possible to adjust servicing intervals and limit wear and tear. Shuttering systems either consist of a metal frame with timber shuttering sheets or are completely made of wood. It is important to distinguish between the two systems as metal has a significant impact on a RFID system.

An appropriate integrative solution for labeling modular shuttering panels within a metal frame is a plastic stopper with a built-in transponder. It can be inserted flush into a hole drilled in the formwork frame. It is essential to collaborate with a manufacturer before implementing this solution, as he would be responsible for drilling the hole and the inserting bushing during the production process.

Nowadays, wooden shuttering boards for formwork on the construction site are labeled with type labels in the form of small wooden plates designed for on-site integration according to the formwork plan. Label transponders can safely be fixed behind these plates. An alternative solution is to screw hard tags (transponders cast in plastic) directly on to the wooden support. Both solutions were tested in the trial runs.

Fig. 6: Labeled modular shuttering systems (hard tag on the left, Smart Label on the right)

Both hand-labeled hard tags and labels beneath the type plates were fixed to the wooden support in order to judge the reliability of the labeling. The labeled components were subsequently taken to the building site and used in the construction work. On being returned to the contractor's yard, they were checked to see whether the transponders were still in place and in working order. Without exception, all the results were positive. Both the hard tags screwed to the wooden supports and the labels fixed underneath the type plates were still intact and produced reliable readings.

3.2.3 Labeling of concrete components

The demand for prefabricated concrete units for use in construction projects is constantly on the rise. They are often custom-made to high precision standards for specific predetermined locations. These units undergo several processing steps from production to warehousing and transportation to the building site before they arrive at their final destination. Many of these process steps can be simplified by attributing certain information, such as a specific number, batch number or lifting and storage regulations to a component. Moreover, the use of these embedded transponders in the ongoing lifecycle of a structure – for maintenance or demolition work, for example – has considerable potential.

3.2.4 Mobile data transmission

It was to feed the constant flow of information from the building site into a centralized computer system that the concept of mobile building data transmission (mBDE) was developed. The purpose of this solution is to forward information on the current construction stage to the digital site information model in real time and to draw up a centralized progress record. Digital planning data can thus be coupled with the actual building site data and serve as a basis for a performance analysis. This solution can support the following scenario: The foreman scans a component on the building site using a hand-held RFID device to check construction progress. If the device recognizes the in-built transponder, the component No. stored on the transponder appears on the display. The foreman decides whether to enter any more information about the component. If so, he can allocate the status (*delivered* or *completed*) and add a comment. The next step might be to record any defects in the form of a descriptive comment backed up with a photo and/or a voice memo.

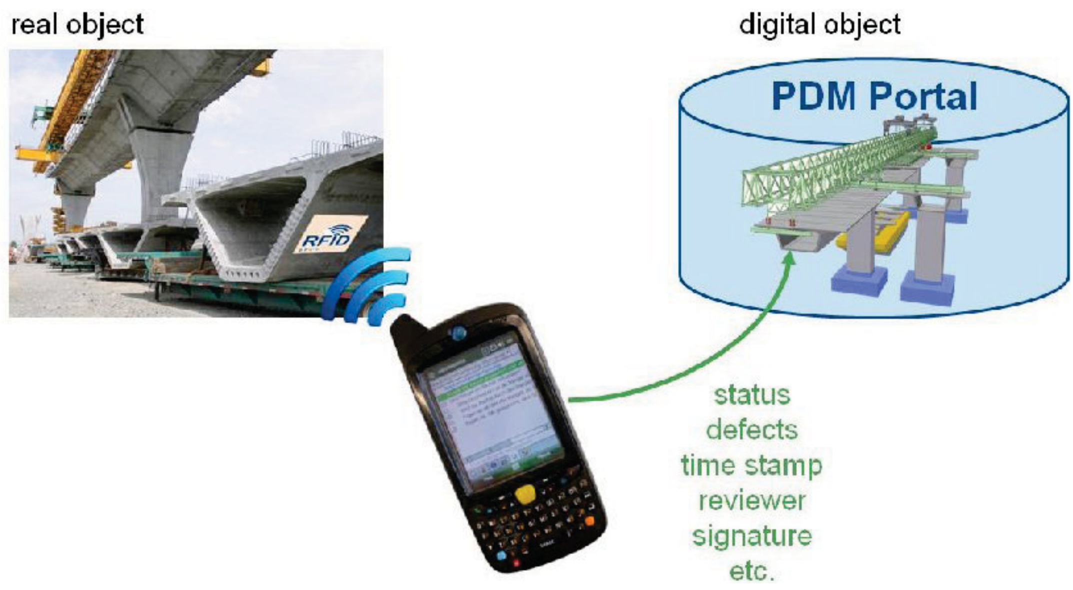

Fig. 7: Concept of mobile building data transmission

The application bundles the recorded component data (status, comment, picture, sound) in an XML file, sends it to the centralized system via a web server and attaches it to the digital component. A product data management system, PDM system for short, is used to record the information. The PDM environment also includes a built-in workflow, which updates the status of the component that was scanned (from *under construction* to *completed,* for instance) and colors in the component concerned in CAD according to that status. So the current status is documented on the digital building site at all times.

3.3 Just-in-time/just-in-position deliveries using last meter construction logistics

To improve material supplies during the execution phase, various logistics concepts were adapted and developed further. The aim is to deliver materials to the exact location where they are to be implemented so as to reduce haulage, search and storage times on the construction site. It was for this purpose that the *last meter construction logistics demonstrator* was devised. It combines RFID technology with satellite navigation to clearly identify and locate materials.

Fig. 8: Graphical user interface of the last meter construction logistics demonstrator (ForBAU, 2009)

Details of the materials to be ordered are sent to a mobile terminal or hand-held device so the foreman or site manager can select them via the graphical user interface (GUI), as required. The precise delivery point is determined with the help of GPS coordinates. This information package is transmitted to the supplier who commissions the goods on order according to delivery location and gives them a clear ID, using RFID transponders. For delivery purposes the driver is also given a mobile terminal, which works something like a navigation system. The mobile terminal guides the driver safely to the predetermined delivery location, where he then proceeds to unload the materials and scan the RFID transponder. Provided they are delivered to the right place, the foreman automatically receives a notification that the ordered goods have been unloaded on the correct spot. On receipt of this notification, the foreman checks the goods and confirms that the contents are correct, whereupon the order details are automatically forwarded to the accounts department for the bill to be settled.

4. Validation of results

In all phases of ForBAU the requirements, concepts and results were validated using real construction sites. Here, the concepts underlying assumptions were reviewed and the feasibility of the developments on the requirements of everyday building practice were tested and optimized. One example is the construction site "Mae West - Effnerplatz" in which a sculpture with about 52 m height had to be built between several buildings in Munich. Ahead of setting up the sculpture, a study of the lifting process of the sculpture with possible collisions was made by ForBAU. For this purpose, data from terrestrial laser scanning, airborne measurements were merged with 3D models from the crane and the sculpture (see Figure 10) and a 4D simulation and animation of the assembly process were implemented.

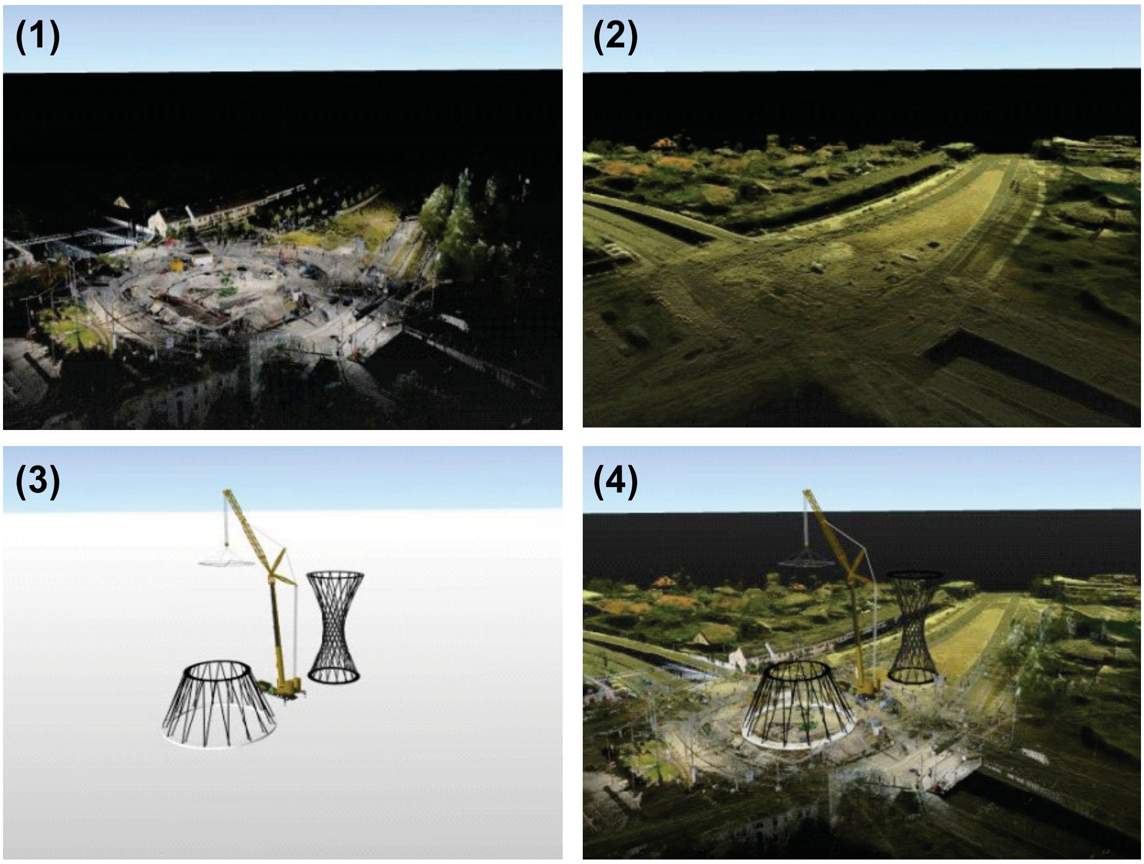

Fig. 9: (1) point cloud of terrestrial laser scanning, (2) point cloud of airborne measurements, (3) parametric 3D model of the crane and the sculpture, (4) point clouds merged with 3D models (ForBAU, 2011)

5. Conclusion

The aim of ForBAU, to create a "digital construction site", was given a strong impulse over the past three years by the advancement and coupling of various technologies. The solution was to apply three-dimensional parametric modeling and discrete event simulation methods to infrastructure engineering. With the help of smart interface programs such as the *integrator*, it is possible to merge various submodels to create a holistic digital building site model. It also involves devising ways of transferring these highly detailed planning data to the construction site, like the *last meter construction logistics demonstrator*, for instance. Here again, it is possible to integrate actual data into the digital site model by the mobile building data transmission concept. The developed concepts were based on construction sites, such as Mae West, reviewed and validated.

Acknowledgements

We wish to express our sincere thanks to the Bavarian Research Foundation (Bayerische Forschungsstiftung) for sponsoring the project and to the partners involved in the project for their huge commitment.

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INTEGRATING THE SIMPLE EVOLUTIONARY ALGORITHM FOR MULTI-OBJECTIVE OPTIMIZATION (SEAMO) AND SIMULATION TO RESCHEDULE ACTIVITIES CONSIDERING WORKSPACE REQUIREMENT

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ABSTRACT: *Workspace conflicts occur frequently during construction process and cause different impacts, especially at the interior construction work when various subcontractors with their different workspace specifications compete on the same given area to complete their job on site. Since the majority of these activities do not belong to the critical path, it is not necessary for quite a number of activities to be finished at a specific time and thus their functional sequence can be rearranged to avoid conflicts. This provides the planner with some kind of freedom to adjust these activities within the limitation of the critical path. The paper proposes a model integrating Simple Evolutionary Algorithm for Multi-Objective Optimization (SEAMO) and simulation to address this problem, in which a simulator has been developed to experiment the schedule in order to discover its properties and the SEAMO has been applied to generate solutions as an approximate Pareto-optimal set. Such the solutions provide engineers with diversified and informed data to support him in decision making.*

KEYWORDS: *Workspace, Schedule, Simulation, Multi-objective Optimization, Evolutionary algorithm.*

1. Introduction

Construction projects are subject to quite a number of influencing factors and are characterized by many unavoidable disturbances. Typical influencing factors in the construction process are workspace overlapping, unavailable material and poor quality of work or delays caused by spatial congestion and/or bad weather conditions. The influences are difficult to predict beforehand, and due to the complexity their impacts are difficult to evaluate by using the traditional planning tools. Usually, project managers deal with these disturbances and uncertainties of construction processes mainly only when they happen, using their experiences, the historical data and "good engineering feeling".

Current project planning techniques are not capable of considering the different influencing parameters of construction operations such as the spatial requirements of construction processes as a resource in their schedules. Consequently, workspace conflicts occur frequently during the construction process and cause different impacts, especially at the interior construction work when various subcontractors with their different workspace specifications compete on the same given area to complete their job on site, such as safety hazards, project delays and cost overruns. Since the majority of these activities do not belong to the critical path, it is not necessary for these activities to be finished at a specific time and thus their functional sequence can be rearranged to avoid conflicts.

Simulation is a powerful decision-making support tool, which allows users to imitate the operation of a real-world process or system over time [Senouci and Eldin, 2004]. With such a tool construction managers can analyze the behaviour of construction operations, detect existing problems such as spatial congestion, and thus the optimal solution can be achieved by comparing the consequences of the different solutions. Although simulation models might enable users to interact with the program through interface to manually develop different schedules, this process is time-consuming and depends on the experience of the user to provide the simulation model with the appropriate input data for developing an actual new robust schedule. However, even an experienced project manager is not able to oversee the complexity of all aspects of the project in advance.

Therefore, this research proposes a model that integrates simulation and Simple Evolutionary Algorithm for Multi-Objective Optimization (SEAMO) to overcome the problem. The simulation process takes a responsibility of discovering the influence of a considered schedule on spatial conflicts and the impact of spatial conflicts on the schedule in return. And according to this information, the SEAMO will generate solutions suitable with the objectives of research, such as schedules which have minimum spatial conflicts and delay of the project. Project managers can benefit from this proposal by investigating a specific part of the schedule or rather the critical activities of the next coming week(s) for time-space conflicts and have some suggested strategies to consider before making decision.

The paper starts by reviewing some important recent developments in construction workspace as well as the Evolutionary algorithm and their application in construction projects. Then it presents the structure of the data model of the proposed methodology. Next the procedure of the simulation process and the application of the evolutionary algorithm are described. Finally, the conclusion and future works will be drawn.

2. Related Research

The literature review is divided into two parts. First we summarize significant work on workspace modelling and analysis. Second we make a short introduction about evolutionary algorithms and their application for problems in the field of construction management.

2.1 Workspace research

Many researchers have been interested in workspace planning and advocated significant works in this area. For instance, Elmahdi and Bargstädt acknowledge the workspace requirements within the schedule plan for good workmanship. Based on literature and site observations, they classified the different required areas in large scale building projects [Bargstädt and Elmahdi, 2010]. With this they propose a semi-automatic methodology to generate the required areas for the scheduled project activities [Bargstädt and Elmahdi, 2010]. The acknowledgement of workspace requirements are developed in a simulation environment. Furthermore, the workspace requirements are embedded as an additional constraint within the software Plant Simulation. Thus the fulfillment of spatial constraints at the construction site can be checked and verified. Akinci et al. developed a methodology to model the construction activities in 4D CAD models, by formalizing the general description of space requirement through a computer system, and built a user-interface tool to automatically generate spaces required by activities [Akinci et al., 2002c]. Later, Akinci et al. extend the concept of generated and assigned workspaces to construction tasks to include a 4D methodology to detect and analyze potential time-space conflicts [Akinci et al., 2002b]. This research provides a methodology to categorize and prioritize conflicts according to their impacts on site. However, it did not account the buffer time of activities in prioritizing conflicts and assumes that activities have fixed start and end dates. And their work also does not provide any solution for the prioritized conflicts.

On the other hand, Dawood and Mallasi advocate a model to detect and measure the severity of space conflicts, which provides a solution strategy to minimize spatial congestion such as changing work rate or using execution patterns. They suggest twelve execution strategies based only on the spatial information of the objects on site. Nevertheless, an execution strategy cannot be changed during the simulation [Dawood and Mallasi, 2006; Mallasi, 2006]. Therefore, their methodology is limited only to the defined execution strategies.

Similarly, Winch et al. suggest two strategies to resolve workspace conflicts either by amending the space required or adjusting the schedule with the "brute force" algorithm [Winch and North, 2006]. However, like Dawood and Mallasi, they did not consider the impact of congestion on duration of activities in return.

2.2 Evolutionary Algorithm (EA)

Evolutionary algorithm stands for a class of stochastic optimization methods that simulate the process of evolution [Zitzler et al., 2004]. The method possesses several characteristics that are desirable to resolve multiple conflicting objectives. The use of Evolutionary algorithms for optimization tasks has become very popular in the last few years with a constant development of new algorithms, theoretical achievements and novel applications [Leitmann, 1977; Stadler, 1977; Fonseca and Fleming, 1995]. Several evolutionary methodologies have been proposed, mainly genetic algorithms (GA), evolutionary programming, and evolution strategies [Back et al., 1997]. These techniques have shown their efficiency in solving problems in a wide domain. For instance, Baesler and Sepúlveda state that genetic algorithms are suitable and reliable in searching for improved solutions [Baesler and Sepúlveda, 2001]. Azzar-Pantel suggests the implementation of GA in solving complex scheduling problems. Furthermore, their characteristics are suitable for solving multi-objective simulation based problems [Eskandari et al., 2005] and they can easily be coupled with any discrete event simulation models [Azzaro-Pantela et al., 1998].

Evolutionary algorithms are based like the aforementioned approaches on a set of candidate solutions. The candidate solutions are modified by two basic principles: selection and variation. The selection principle reduces the competition for reproduction and resources among living beings. The variation principle imitates the natural capability of creating new generations of beings by means of crossover and mutation. Although the underlying mechanisms are simple, these algorithms have proven themselves as a general, robust and powerful search mechanism [Back et al., 1997].

Genetic algorithm is a subclass of the evolutionary algorithms and has been applied for problems in construction management. For instance Senouci et al. propose an augmented Lagrangian genetic algorithm model for resource scheduling [Senouci and Eldin, 2004]. Osman et al. use Genetic algorithms to optimize the location of temporary facilities on site [Hesham M. Osman et al., 2003]. Similarly, Zhou et al. demonstrate how the site layout process can be automated for specific types of construction. They integrate a general simulation approach for modelling space, logistics and resource dynamics to optimize the layout based on various rules and constraints [Zhou et al., 2009]. Mallasi et al. propose a genetic algorithm approach to search for the most suitable execution pattern for a construction activity [Mallasi and Dawood, 2003].

3. Data of the Model

The data model of the proposed concept in this research consists of the process data, the product data and the productivity data. The process data is the schedule data, for instance, from MS project. It contains attributes about the whole schedule such as the total slack as well as specific task attributes such as the task name and duration. The product model contains two types of information: the 3D components of the model, in which each component has a unique element ID and its location in (x, y, z); and workspace data which describe the required workspace such as location and size of the area. However, it should be mentioned that not all activities must have product data. The productivity data presents the impact of congestion on productivity and thus may cause delay duration of activities when spatial conflicts occur. The two later types of data are just required for activities that are considered to be important in investigating the conflicts of workspace.

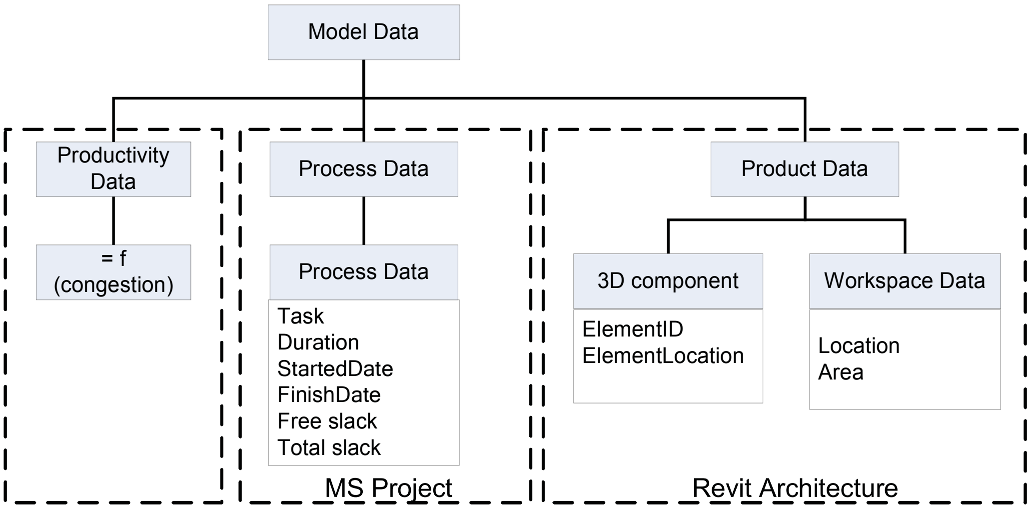

Fig. 1: Data of the Model

Since construction management is usually accompanied by huge, complex and uncertain information, and the reliability of results that come from a simulation model depends on the level of detail and the exactness of data, so this model is not suggested to apply to a whole construction project. Instead, it is applied to investigate an assumed area of congestion, a "hot spot" of the project, such as for interior activities of a typical floor area. Such investigation may ensure the necessary detail and level of data for the simulation process.

To adapt to the application of the model, the overall process data is required for a whole project but the product data and the productivity data are just needed for activities which belong to the investigation phase. The necessity of process data for all other activities of a project is to investigate the dependencies of activities, as they are adjusted, on each other and on the whole project; whereas the product data is used to analyse and calculate spatial congestion; and the productivity data is used to determine the delay duration of activities due to spatial conflicts.

4. Research Methodology

The aim of the research is to find out a set of schedules which satisfies the following three objectives: (1) to minimize total spatial conflict of the schedule, (2) to minimize spatial conflict between any two activities, and (3) to minimize delay of the project caused by spatial conflicts. The method proposed in this research considers the objectives equivalent, none of them is more important than the others, and produces an approximate Pareto-optimal set. A solution is called Pareto-optimal if it will not be possible to improve the value of any one of the objectives without simultaneously degrading the quality of one or more of the other objectives (figure 1) [Abraham et al., 2005].

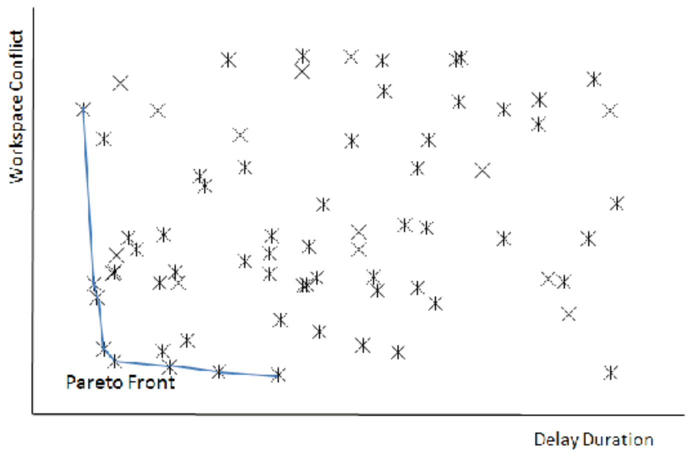

Fig. 2: Concept of Pareto optimality

To reach an approximate Pareto-optimal set, the method combines SEAMO (the Simple Evolutionary Algorithm for Multi-objective Optimization) and simulation which is described in figure 3. The simulation process responds to experiment a schedule in order to discover spatial conflicts, impacting of conflicts on the due date of the project. And the goal of SEAMO is to generate a widely and evenly spread population of schedules as close to the Pareto front as possible.

4.1 Simulation Process

The input data for this process contains: 1) the schedule of a project; 2) index of activities within the schedule which need to be investigated concerning spatial congestion (considered activities - CA). According to these activities, an investigation duration (T_1,T_2) will be identified. There, T_1 is the point of time, where the Considered Activities (CA) start and T_2 is the point of time, when all CA finish. It is noticed that T_2 can be changed during the simulation process; 3) the location of products and spatial requirements responding to each considered activity; and 4) impact factors of workspace conflicts on productivity (PRF - productivity reduction factors) responding to each considered activity.

In order to analyse the properties of schedules, the research uses a discrete-time simulation model, in which the chosen interval is one working day. At one point of time t, according to the experimented schedule, all activities which belong to CAs and occur at time t will be identified; these activities will be listed in a list $Tasks_t$. Then, spatial conflicts between two arbitrary activities in $Tasks_t$ will be quantified. Afterwards, regarding to the area of spatial conflicts and PRF of activities, the duration of activities will be extended. On this process, if both activities have total slack bigger or equal to zero, then each one will get one half of the conflicts assigned; otherwise, the one with total slack bigger than 0 will be impacted by the conflicts. Finally, the schedule and T_2 will be updated due to the extension of the activities' duration, and the next point of time (t+1) will be investigated.

The output of this process will be: 1) the maximum value of one single conflict between two arbitrary activities (single conflict); 2) the total conflicts within the schedule; and 3) the delay duration of the total project due to workspace conflicts.

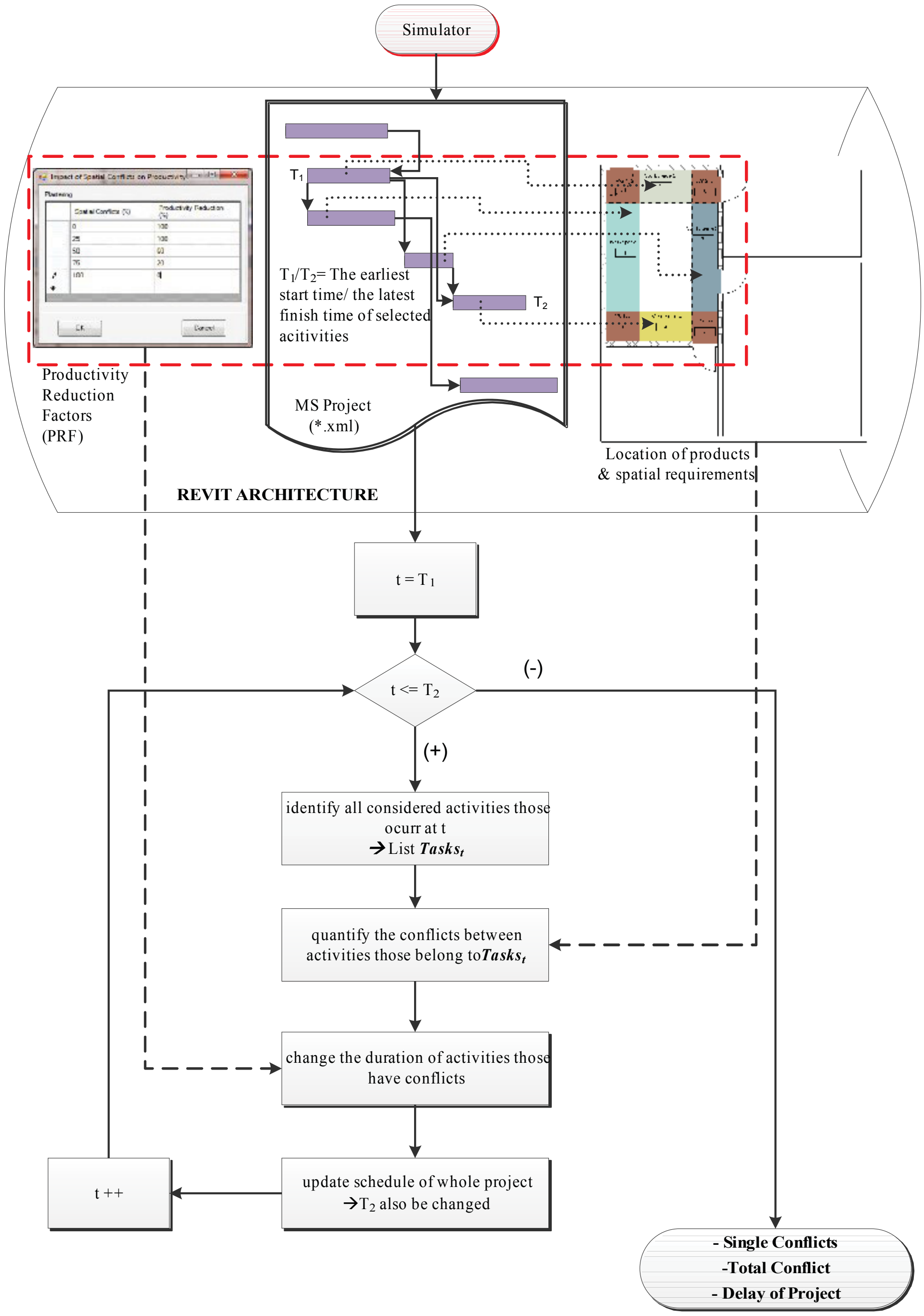

Fig. 3: Simulation Process

4.2 Application of SEAMO in Rescheduling

The Simple Evolutionary Algorithm for Multi-objective Optimization (SEAMO) is a Pareto-based multi-objective evolutionary algorithm. It uses a replacement strategy to move the solutions during the searching process ever closer to the Pareto front, and to widen the spread of the solution set [Abraham et al., 2005].

The searching process begins with generating an initial population of schedules; then, each individual of the population breeds with a random individual to create an offspring (that means crossover rate is 100%) and to apply a single mutation to the offspring. If the offspring does not satisfy constraints created in the scheduling, it will be repaired. After that, the simulation process will be executed to evaluate its objectives. Based on these values, the replacement strategy is implemented to decide which one of parents or the offspring can exist in the population. After all individuals in this generation are selected for breeding, the next generation will be generated and the crossover, mutation and replacement will be applied again. This process will be continued, until the expected number of generations is exceeded. After the searching process finishes, a set of schedules will be chosen to be presented to the engineers, who can base their decision on them.

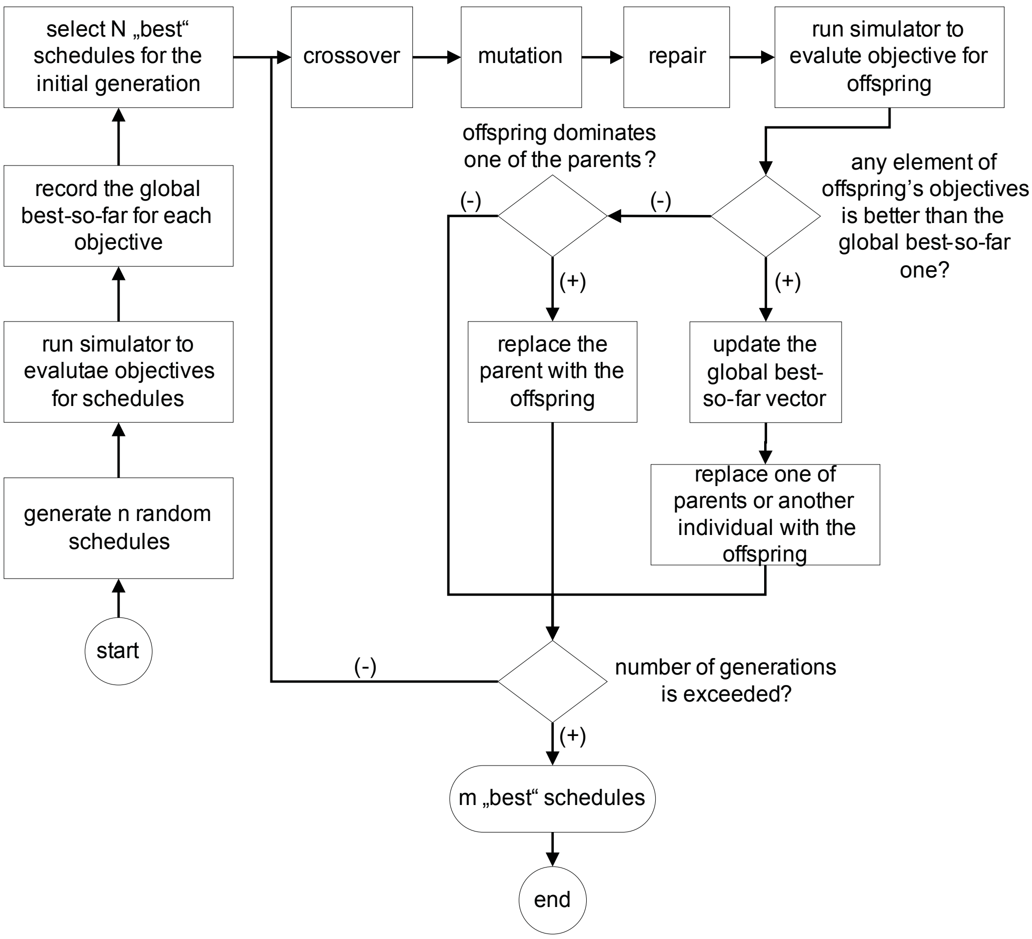

Fig. 4: Application of SEAMO in rescheduling

In order to reduce the searching time, the initial population used in this model is not totally random. At first, n random schedules will be created. It is noticed that only CA will be selected to move randomly within their total slacks during the generating of the random population. Once each activity is moved, the total slack and its successors will be updated according to their constraints. Then the next random value for the following activity is created. Therefore, after this step, the delay duration of the schedule is still zero. Next step, the simulation process will be applied to evaluate objectives of the schedules, and the Pareto front of this group will be identified. N schedules which are closest to the Pareto front will be chosen for the initial generation.

Afterwards, simple crossover and mutation operators are applied to generate offspring. From two parent schedules, a crossover position is randomly chosen, the first parent will provide the first part of schedule for the offspring, and the second will provide the rest. And then one other position (x), number of activities (n) and the day to be changed (t) will be randomly chosen for a mutate process. Notice that t may be negative or positive. The mutation operator will be then applied for n continuous activities from the position x. These activities will be moved t days uniformly.

After crossover and mutation operators, no guarantee that the relation of activities of the offspring still satisfies original constraints. So the offspring must be repaired before evaluation with the simulator. In this repair process, activities will be moved to as close to the current positions as possible, which still satisfy constraints and ensure that the delay duration of the project is zero as well.

The replacement strategy in this model is quite simple. Normally, the offspring will replaces one of its parents if either it dominates one of them (i.e. at least one of its objectives is better than the parent's and none of its objectives is worse than his), or one of its objectives can improve the global best-so-far solution vector. However, in the later case, if the global values occur in both parents and the offspring does not dominate them, then the offspring will replace a random individual in population. In addition, if the offspring is the same as one individual that already exists in the population, the offspring will be deleted.

5. Conclusion and Future Work

The goal of this research is to find a series of strategies that satisfies three criteria: to minimize the total spatial conflict of the schedule, to minimize the spatial conflict between any two activities, and to diminish the delay of the project caused by spatial conflicts. The integration of simulation with evolutionary algorithm has been successfully achieved. Like other results from random search techniques, different schedules given through the proposed method in this research are really "diversified". Therefore, decision makers can chose the suitable solutions depending on their individual conditions such as crew size and material quality and quantity, etc.

Besides, project managers are able to evaluate solutions efficiently and make their decision based on the proposed methodology either for the whole schedule or for a selected part of the schedule (short term activities). However, the authors recommend the use of this methodology for the short term activities, since investigating the whole project is too time consuming and still requires too much detailed information.

In the future, an animation tool should be developed to help decision makers to investigate the schedule and its conflicts visually. Also, the detail level of workspace assignments and the impact of workforce conditions should be considered.

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3D VISUALIZATION OF ACCESS ROAD CONSTRUCTION IN WIND FARMS USING INTEGRATED 3D MAX AND VITA 2D

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ABSTRACT: *The environmental deterioration all over the world created a need to find alternative resources for energy, one of which is the wind energy. The increase in wind turbine construction to use wind energy as an alternative resource creates a need to develop tools that can help in performing decision making in an easy manner based on the thorough understating for the processes involved in wind farms construction. In the domain of operations design and analysis, the ability to see an animation of simulated processes would help in verifying the simulation model assuring that there are no errors in the model. Wind farm construction is a repetitive construction process that mainly involves lifting large prefabricated components to large heights and the construction of access roads to support equipment during construction and in maintenance of wind towers during operation. Contractors are faced with challenging work environments that involve time, cost and safety of operation. Therefore simulation could be considered as a useful tool that imitates what happens in reality and can be used afterwards in animation. This paper presents a discrete event simulation model using stroboscope simulation tool to simulate the construction process of wind farms. The model uses rhinoceros as a tool to relate how using different routes and paths of access roads in construction could affect the duration and accordingly the cost. In addition animation of wind farm construction processes is presented using a customized vita-2D output trace file in integration with a special written 3D max script to produce a three dimensional animation.*

KEYWORDS: *wind farm construction, 3D animation for wind farm construction, simulation of wind farm construction.*

1. Introduction:

This ambitious growth in wind power requires a significant ramp-up in all links of the wind turbine supply chain. Wind turbine construction is one of the most critical yet under-investigated steps in the supply chain of wind turbines. Wind turbine construction is a repetitive construction process that mainly involves constructing access roads for the wind towers that will be built and lifting large prefabricated components to large heights in high wind speed conditions. Thus, contractors are faced with challenging work environments that impact the time, cost and safety of construction operations. An important factor affecting project schedule and costs is the transportation and road system that exist in the wind farm. Roads have to be constructed such that they can adequately bear the load of wind turbine parts. Finishing construction of access roads in short time and less cost may cause a considerable decrease in the total cost and duration of the construction process. Furthermore, wind farm sites are typically selected in areas of high wind speeds. High wind speeds pose specific problems during the erection of wind turbines (Carns and Bender, 2009).

Research in wind energy has given little mention of the challenges facing the construction of wind turbines. From a life cycle perspective, most of the literature has focused on the planning, design, and operation phases of wind turbines. Wind turbine construction is a critical link in the supply chain of wind energy, yet little is documented about the challenges facing contractors during the construction of wind farms.

The main objective of this research is to develop a discrete-event simulation model that can be utilized by contractors in wind farm construction and to utilize a tool to determine the effect of using a certain path or route in construction of access roads on the duration of some operations and accordingly on the overall duration . The model would be used to select best routes to start the construction operation and optimum number, combination and types of resources to use. In addition, this research aims at investigating the number and type of equipment and/or resources that could affect the construction operation and implementing a 3D visualization using a customized file from the same simulation tool used in simulation.

2. Wind Farm Construction and the Developed Model:

The construction of wind farms can be divided into four main parts: Earth moving before road construction (rough grading), roads construction (access roads), foundation and electrical works (utilities and services) and, wind tower construction (erection). Figure 1 shows a flow chart that represents the different phases involved in the construction of wind farms with some figures that represent the real work that happens in the construction site. Figure 2 shows the complete stroboscope model of the entire operation (without the additional embedded stroboscope code) and Table 1 shows the description of these activities. The simulation network consists of rectangular and chamfered rectangles called “COMBI” and “NORMAL” activities while the resources can be represented by circle shapes named “QUEUES”. The COMBI activities have queues to support them. More details about STROBOSCOPE can be found in Martinez 1996. The basic idea of using STROBOSCOPE is its ability to create multiple replications for the various alternatives that would affect the simulation time.

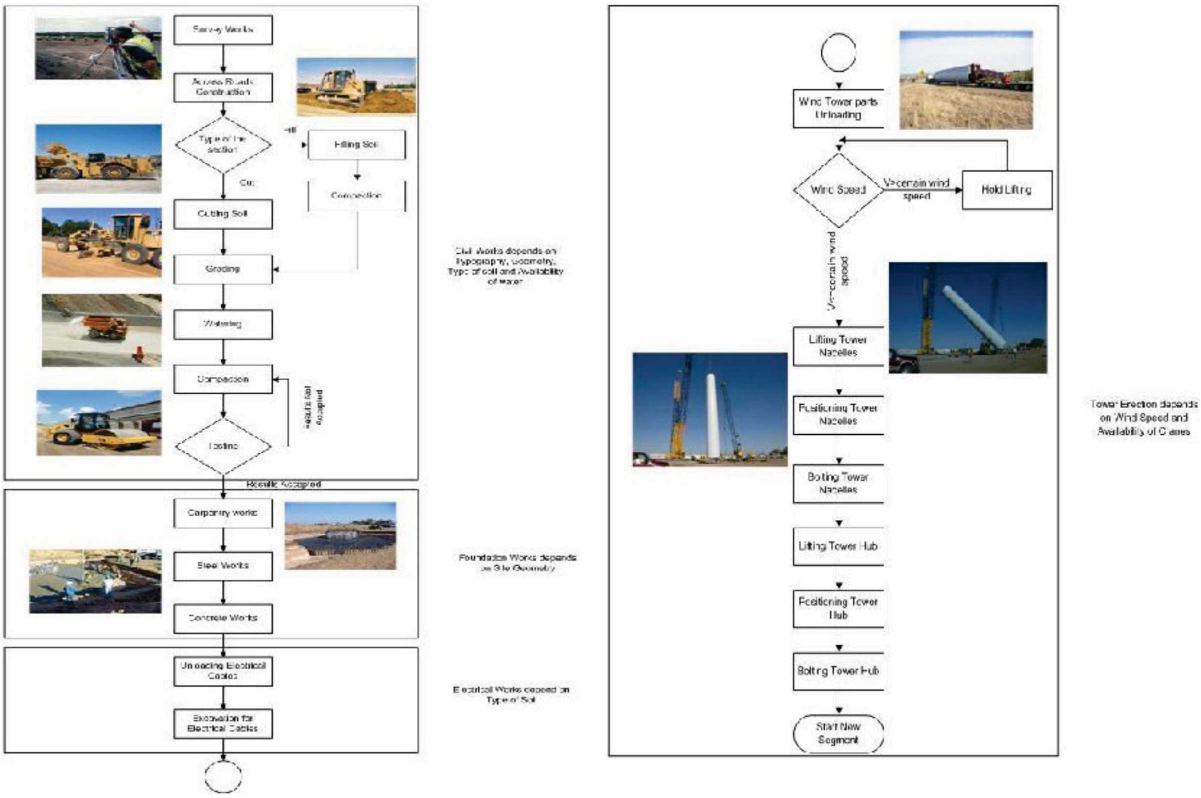

Fig. 1: Flowchart showing different phases involved in the construction of wind farms

The basic idea behind the developed stroboscope model was to deal with the cutting and filling of soil in earth moving operations into two separate operations. This was done by introducing a resource called "*RdSgmnts*" which contains all the segments that are required to get cut and filled. The resources in stroboscope can be either generic which are simply a pile of resources in a queue or simple characterized resources which are resources under the same name but inside the queue the resources have multiple subtypes that can have different properties. This was useful in our case because the different stations or road segments that were required to get cut and filled were considered as subtypes for the queue *"RdSgmnts"*, these stations or subtypes had two properties. The first

Property called value and describes the quantity of soil that will be cut or filled, while the other property is called cf which can be considered as a binary code. For road segments having a value of cf=0 the section was considered as a cut section and for road segements having a value of cf=1 the section was considered a fill section. The syntax for the previous can be written as follows:

```
CHARTYPE Stations cf value; /ST
SUBTYPE Stations st1 1 200;
SUBTYPE Stations st2 0 400;
SUBTYPE Stations st3 1 800;
```

A DYNAFORK (which is a STROBOSCOPE element used for routing resources) was used after the sections were available in the QUEUE *"RdSgmnts"* to route the segments to be constructed based on the value of "cf".

The syntax for the previous can be written as follows:

```
STRENGTH RC1 'RdSctn.cf == 0';
STRENGTH RF1 'RdSctn.cf == 1';
```

The operation of cutting the road differs than that of filling and the duration for these two operations differ due to the difference in the productivity of equipment used in each operation. In case of cut work in a particular section, the loader starts to cut the soil from the road segment until it reaches the stake limiting the road corridor. So for this operation a loader was used and a truck to dump the hauled soil. As for the fill section the technique depends on filing the section on 25 cm layers and then compacting this layer before starting the next 25 cm layer and the same struck that was used and loaded by loader in the cutting operation is used in the filling operation. To relate the duration to the amount of soil that each operation takes, two variables were defined. The first variable called *"NoScoopsPerHauler"* which is the number of times the loader loads the hauling truck until the trunk is full (in case of cutting operation). The second variable is called the *"CycleDur"* which describes the duration in which the loader loads the truck. By dividing the amount of soil by the number of scoops per hauler and multiplying the result by the cycle time, this would give the total duration as a variable in soil quantity. The syntax for the previous was written as follows:

```
DRAWDUR RC2 'RC2.value';
DURATION CtgSoil '(RC2.SumDrawDur/NoScoopsPerHauler)*CycleDur.'
```

3. Analysing a Typical Wind Farm Construction Project Using the Developed Model:

In this section we present the different types of analyses that could be generated using the model. Basically, there are two main functions of the model. It can be used to assess different construction alternatives and their impact on cost and time. Secondly, it can be used in developing a 3 dimensional animation for on-shore wind farm projects.

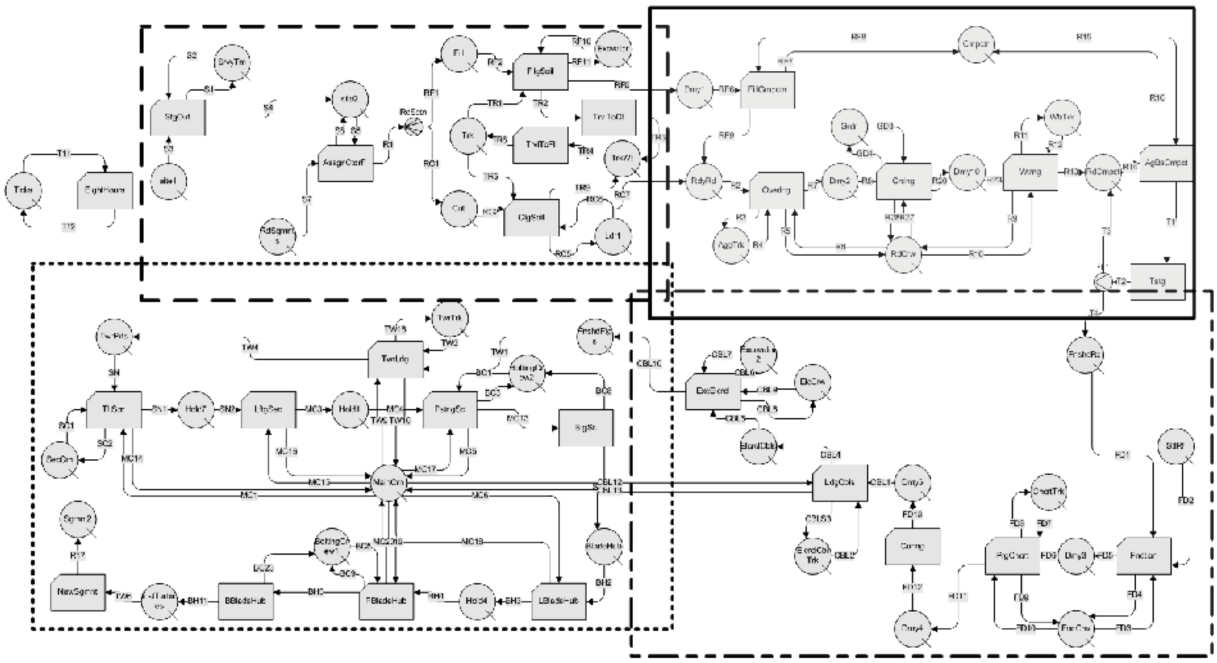

Fig. 2: The Proposed Simulation Model

Model Entity	Description
GntryPrts	A queue that represents the parts of the gantry system used in supporting the form-works of the bridge deck
GrdrAssmbly	Combi activity of assembling the gantry system parts
Grdr	A queue that represents the finished assembled gantry system ready to get launched
PsntgGrdr	Combi activity of positioning the girder on the brackets supported on the piers of the bridge
PrsFrms	A queue that represents the parts of the piers forms
PrsCnstr	Combi activity representing the activity of constructing the piers of the bridge
GrdrPst	A dummy queue that has the gantry system positioned and ready for form works and steel reinforcement
AdjFrm	Combi activity for the adjustment of formworks
Crn	A queue that has the crane used in different tasks in the bridge construction
FrmCr	A queue for the form crew that is used in adjusting the forms
StlRf	A queue that represents the steel reinforcement used in reinforcement of the bridge deck
LftgStl	Combi activity representing the process of lifting the steel bars used in reinforcement
BtmFrms	A queue that representing the bottom forms that were constructed by the form crews
Rebar	Combi activity for the reinforcement of the bridge deck
StlCrw	A queue that representing the steel crew
Rnf1	A queue that represents the bottom reinforcement
CncrtArrvl	Normal activity that represents the arrival of concrete
Trk	Queue representing concrete trucks or containers
FllgPmps	Combi activity representing filling of the pumps prior pouring starts
Cncrt1	Dummy queue that transfers the concrete resource
PrgCncrt1	Combi activity that represents the pouring of concrete in the web and bottom part of the girder (assuming it is a box section which is usually the case)
PrdWb	a queue that represents the poured concrete section of the web of the bridge's girder
Curing1	Normal activity for curing of the poured section and consuming time to attain the characteristic strength required and removing the formworks
CrtCr	A queue that represents the concrete crew
FnshdWb	A queue that represents the finished web section and the bottom of the girder
DsmntlgFrms	Combi activity of dismantling the forms to use in the top formworks of the girder
TpFrms	Dummy queue that holds the formworks until pouring concrete starts
Dck	A queue that represents the deck formworks ready for pouring concrete
PrdDck	Queue representing the poured deck
FshdSpn	Queue representing the finished spans
Prstrg	Combi activity representing the prestressing of the post tensioned steel
LwrgFrmWk	Combi activity that represents the lowering of form works to move to the next span
MvgToNxtPr	Normal activity to move the gantry system to the next span
MvgBrkts	Normal activity to move the brackets supporting the gantry system to the next span
LwgGrdr	Normal activity to lower the gantry system to start an new segment
Sgmnt	An empty queue that represents finished number of spans

3.1 Assessing Alternatives that Might Affect the Construction Process:

The wind farm construction process can be affected by three main parameters; the access road routes, the number and productivities of the crews and equipment and, the erection techniques of the towers. Exogenous variables include the topography, the wind speeds and the site geometry

3.1.1 Access Road Routes:

Figure 3 shows how the different paths chosen for the access roads could result in different volumes and locations of cuts and fills that would in turn affect the simulation time. Because of the fact that the volumes of cut and fill are different across the various stations, the duration distribution of the earthwork activities will also be different which will have an impact on the overall duration of the project. This impact cannot be easily calculated or understood without a detailed simulation model such as the one developed in the previous section. The Figure shows the effect of choosing a certain path on the simulation time; this was done by running the different volumes resulting from 4 hypothetical paths on a randomly generated surface and observing their effect on construction time while using different number of trucks.

Not only does the amounts of cut and fill sections in the roads required to get constructed would affect the duration; but also the shape and profile of this section. Power required for equipment used in hauling depend on the rim pull which is the power needed by a truck to overcome both the rolling and the grade resistance. The rolling resistance wouldn't be a governing factor because it depends on the soil type and in the same construction site the soil type would be nearly the same. As for the grade resistance the duration would be affected depending on whether the grade was uphill or downhill and even for the two different alternate sections having a grade segment uphill, the duration would be affected based on the percentage of the uphill in the two segments.

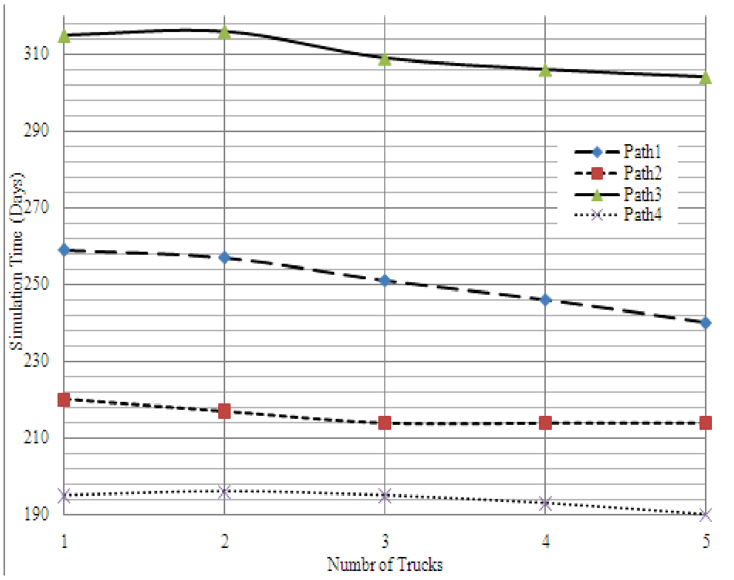

Fig. 3: Different Paths and Trucks and their effect on simulation Time

To model the above 3D modeling tool (Rhinoceros 3D) along with its graphical algorithm editor (Grasshopper) was utilized to analyze the effect of using different paths in constructing the access roads in on-shore wind farm construction sites.

Rhinoceros is a NURBS (Non-Uniform Rational B- spline) based 3D modeling tool. Rhino's increasing popularity is based on its diversity, multi-disciplinary functions, low learning-curve, relatively low cost, and its ability to import and export over 30 file formats, which allows Rhino to act as a 'converter' tool between programs in a design workflow. On the other hand Grasshopper is visual programming language. Programs are created by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components.

The first step is to import the construction site into Rhino as a surface which can be created by various ways. Then this surface is introduced to Grasshopper through a surface component.

By this we have already defined the construction site and we need to define the access road route, this is done by defining control points along the route, usually end points and points of horizontal direction change, then connecting between these control points by straight lines. The control points are essentially lying on the surface while the connecting lines lies in the Euclidean space. In order to get the actual path between these points we project the connecting lines on the surface, so we get the route that follows the surface terrain and then we can also calculate the actual length of this route.

After defining the route we run into the analysis process, which, in this case, is dividing the route into segments then calculate the slope of these segments which will be used to calculate the grade resistance of each segments and determine the travel time of each equipment along this route.

This is done by evaluating the curve representing the route, evaluating the curve means that we consider the curve as a domain (D) between the start and the end points then we get a set of points (P) belong to that domain and at certain parameters (t), i.e. t {0.2D, 0.4D, 0.6D,…}.

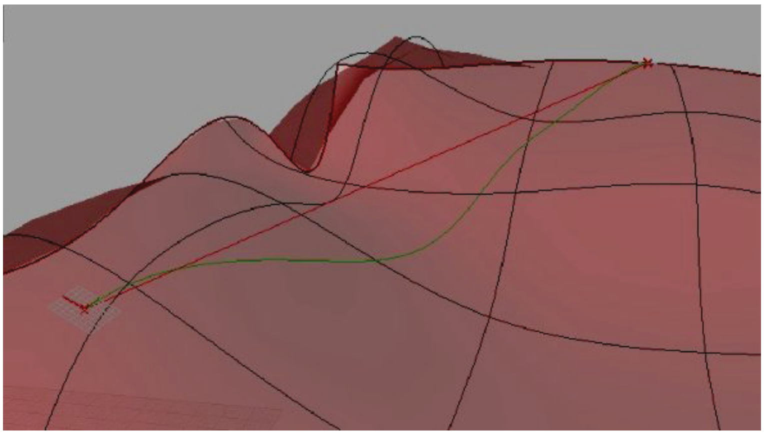

Fig. 4: The modeled surface, control (end) points, the line connecting them and the line's projection on the surface.

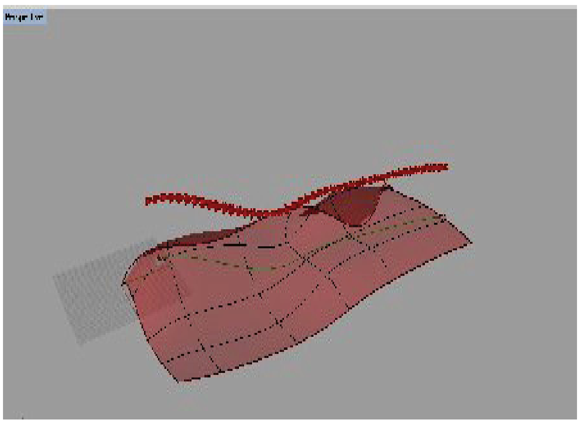

Fig. 4a: Model Surface from south west view

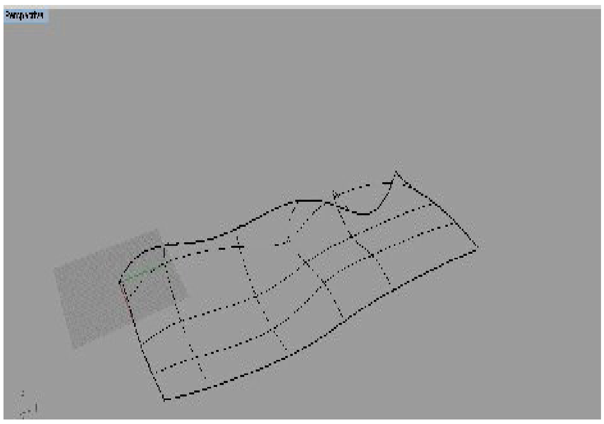

Fig. 4b: Model Surface from south west view

Beside getting the points at the desired parameters, we also get the tangent vectors at these points and distance along the curve from the start point to the each of the evaluation points.

The number of the evaluation points is decided by the user and decided based on the desired resolution and accuracy. After that we get the slope between each two points pi and pi+1 from the following relation:

Slope = 100 [(zi+1 – zi) / x]

where

zi+1 and zi are the elevations of the points pi+1 and pi
x is the Euclidean distance between the two points

Finally the resulting slopes are exported to excel to calculate the grade resistance for further duration calculations.

After data are exported to excel each segment has a value determining whether this section is cut or fill, the amount of soil and a value to determine the grade resistance of this section. Grade resistance is expressed as a speed for the equipment which will be translated into duration. The time taken by an equipment to move on an uphill grade would be less than the time taken by the same equipment on a downhill grade. Also the duration that the equipment will take to move on an uphill grade would take more time than that of another uphill grade but with a less value.

The above shows that selecting a certain path would affect construction time due to the different stations having different cut and fill volumes and also different grades.

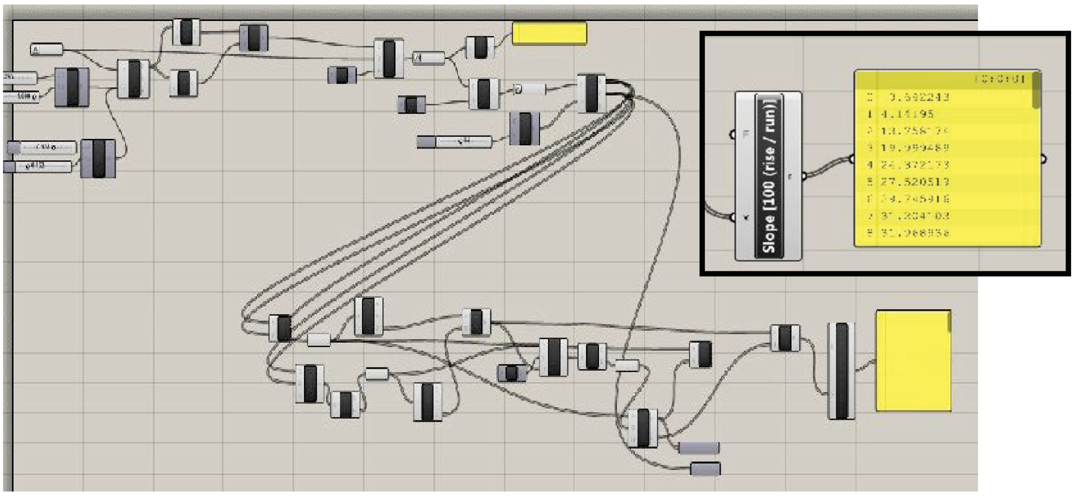

Fig. 5: Grasshopper definition and the resulting slopes

Figure 6 shows how certain grade would affect the construction time of a certain segment. The chart was created by calculating the different grades for the different segments and calculating the equivalent grade resistance that the equipment need to overcome the both rolling resistance and the grade of the road. The resistance and the power needed by the equipment is then used to determine the velocity of that equipment. then using the equipment velocity and knowing the length of the segment the duration of the operation can be easily calculated.

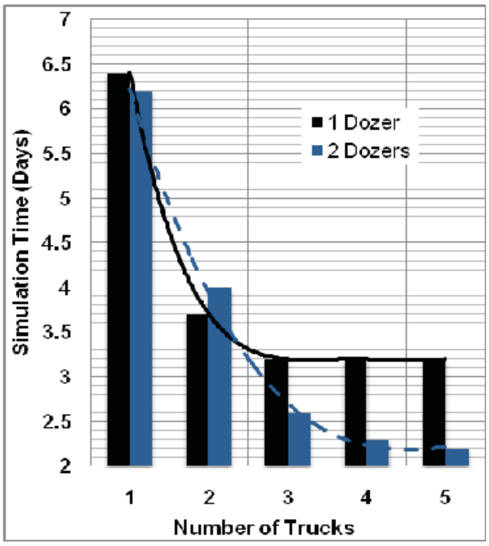

Fig. 6: Number of trucks versus simulation time with different number of dozers

3.1.2 Equipment and resources

Different combinations of resources and their influence on the simulation time and cost can be evaluated. Figure 6 shows how one can assess the simulation time for one access road station using up to five trucks and two dozers for example.

Another form of results is the number of times a certain resource is used all over the simulation time and in that scenario it would be easy to determine the rate by which this resource is used. In addition to the above it could be easy to observe the number of resources inside the queue at any instance over the simulation time and the rate by which this resource is utilized.

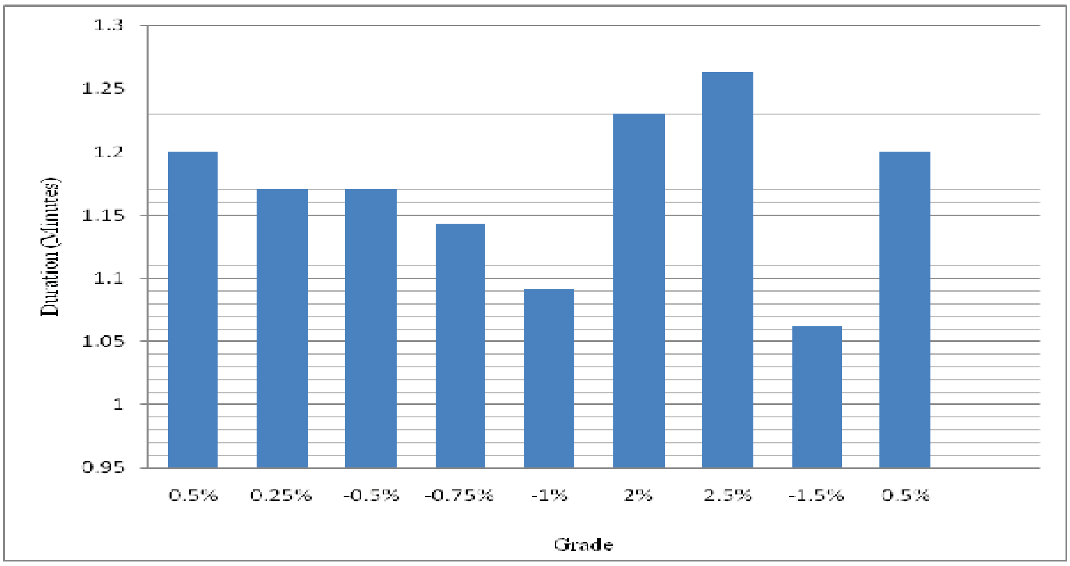

Fig. 7: Different grades and corresponding duration

Figure 7 illustrates the distribution of the truck in the queue of the resource truck over the life time of the resource. The figure shows the truck number is ranging between 0 and 5 because five trucks were used in the simulation to plot these results. The trucks keep entering and leaving the queue until they reach zero trucks in the queue which means that all the trucks are used. The solid line shows a 3-period running average.

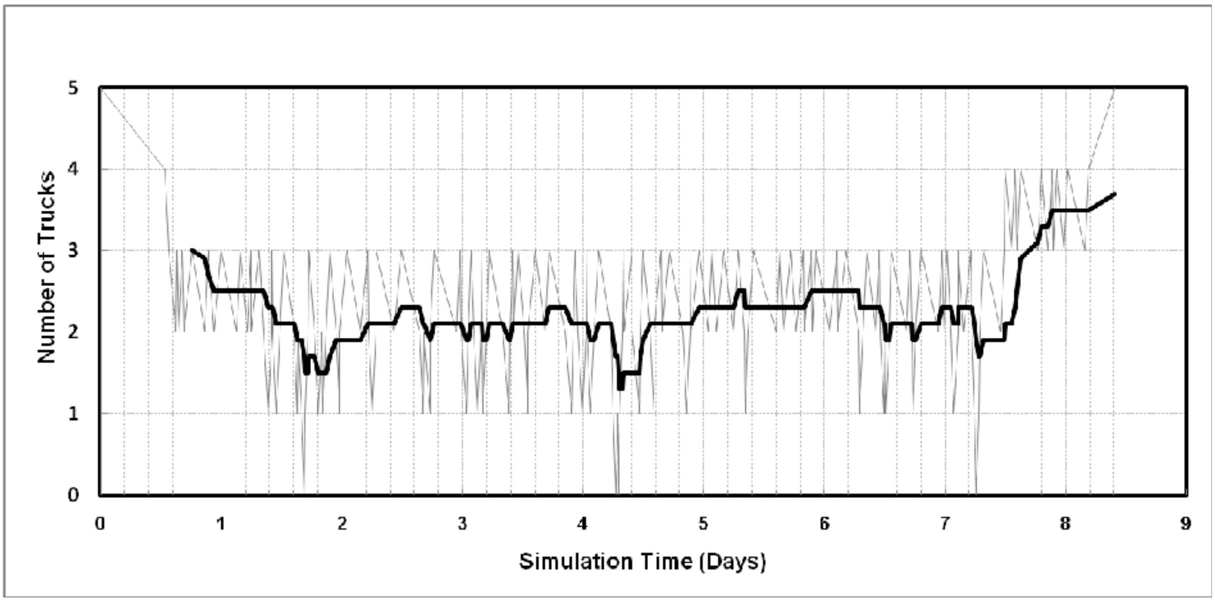

Fig. 8: Distribution of number of Trucks in resource queue over period of using this resource

3.1.3 Erection technique for the towers:

The method of erecting towers as previously mentioned can be divided into two approaches, the first is called the ground assembly approach where the blades are connected to the hub on ground and then lifted by cranes to the top of the tower. The other approach is connecting the blades to the hub on the top of the tower and this is called tower assembly. In each of the two approaches there are two available alternatives, the first one is using a single crane to get the whole job done or using two cranes, a main crane and another supporting crane. In this model two cranes are used simultaneously to get the tasks done. Both of these techniques could also be evaluated for any project to assess the impact on cost and duration.

4. 3-D Visualization:

Discrete-Event Simulation (DES) is a powerful objective function evaluator that is well suited for the design of construction operations. DES as applied to construction operations planning and analysis entails the creation of schematic process models that represent how construction operations will be performed. These models consider the different resources that are required to carry out the construction operations, the rules under which the different tasks that compose the operations are performed, the managerial decisions made during the operations, and the stochastic nature of events. Vita2D is a post-processing animator hosted on Microsoft Visio. It creates, moves, and modifies objects in a drawing according to instructions in a trace file that is written according to the Vita2D language specification. Vita2D attempts to maintain a constant ratio of animated time to the time specified in the instructions. Vita2D trace files are typically generated by discrete-event simulations when they run. (Martinez, 2007)

The animation generated uses a Stroboscope simulation model. It is also possible to create some short animations by typing directly the trace file instructions. Construction operations are, rarely performed on one, flat, planar surface. Although effectively used in communicating some modeled construction processes, 2D animations inherently lack the real-world, 3D features that are indispensable to convincingly animate most construction operations. In particular, due to the degrees of freedom exercised in performing most construction processes, it is hard to accurately portray construction in two dimensions. The out files used in 2D visualization were used in cooperation with 3D max to animate the process in a three dimensional view. A script for 3D max was written at first, the script begins with defining the paths and objects that will be animated. In three dimensions there are different types of object motion, such as controlling them by the standard "Position X Y Z "controller" or "position expression" in which mathematical expressions are used or "noise position" which adds noise to the motion. In the file used for animation of the model "The Path Constraint" controller is used which limits the motion of the object along a predefined path, with some settings of motion smoothness and timing in the motion using some options. Then the object position controller, paths are assigned to a new variable. To integrate the previous script with the outfile of stroboscope used in animation, minor modifications were introduced such as converting the advancement time for the activities into percentiles and leaving a single space between each statement and the one that follows it (El-Masry, 2011).

5. Conclusions and Discussions:

Due to the adverse impacts of using conventional energy resources, new techniques are presented to produce clean energy that help in sustainable development such as wind power. Wind power is used to produce electricity by wind farms which consists of multiple wind towers. A framework that can be used in planning and decision making to help and assist contractors in deciding which equipment and access road route to use while constructing wind farms is presented using a simulation tool called stroboscope. The simulation model simulates the various tasks and processes involved in wind farm construction. Different forms of outputs are presented that can help in deciding the factors that could affect construction. To reflect the effect of using a certain route in construction of access roads a 3D modeling tool (Rhinoceros 3D) along with its graphical algorithm editor (Grasshopper) were used. The tool was used to model the different paths that can be taken and how the grade of the path would affect the velocity of the equipment and by its part would affect the total duration of the operation. The paper discussed the development of a 3D visualization tool that can help in visualizing the different operations in construction and help in getting an understanding of how the equipment interact with each other which can be useful in the tight sites.

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ANALYSIS OF THE CONCEPTUAL INFORMATION SCHEMA FOR MULTIPLE INFRASTRUCTURE LIFECYCLES

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ABSTRACT: *This paper discusses the schema of infrastructure information in order to explain its meaning and role in infrastructure lifecycles. The schema of infrastructure-information can be represented in the form of a pyramid diagram in an abstract-concrete scale, and an information lifecycle can be divided into five periods: fetal period, young age, youth, mature age and old age. In the infrastructure-information pyramid, ideas are placed at the top and are related to specific infrastructures below via policies and other parameters. The big pyramid constitutes a holistic body together with people, region, climate and natural environment. In the spatiotemporal schema of the pyramid model, information technology is represented as acquisition, representation/processing, prediction, projection, life management, operation, communication, and information management. This paper also discusses how VR/AR technologies work in this schema.*

KEYWORDS: *Information structure. Infrastructure lifecycle, pyramid schema, virtual reality, information management*

1. Introduction

What is information in the infrastructure lifecycle? How does information work in the lifecycle? Discussions on information are made concerning information technology but no full discussions are made about the essence of information. From a viewpoint of informatics, reshaping all the disciplines in terms of "information" and developing a system of information schema are required. In the field of civil engineering as well, it is necessary to consider the information on infrastructure from a viewpoint of informatics and to identify its order and schema for seeking the future role of information and the direction of technical development.

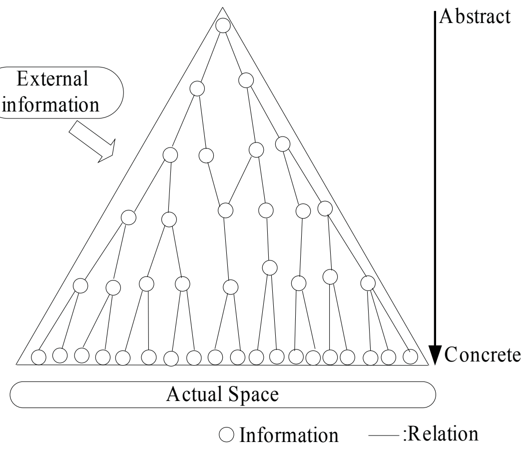
Although we use various kind of information technology in the conventional process in construction, few frameworks of information have considered so far. In recent years, as building information models (BIMs) are developed in ordered to describe the information of buildings (ex. Lee, et al., 2006), the importance of information models come to be appreciated. However, the current BIMs target only for physical models of buildings not for whole information systems including ideas, concepts, or politics.

The author has started to discuss the significance and role of information in infrastructure lifecycles (Makanae, 2010). In this paper, the author discusses the position of information in the construction process of infrastructures and the spatiotemporal schema of information. Also discussed is a flow of new information that relates infrastructures to people and society. Finally, this paper discussed how virtual reality (VR) and augmented reality (AR) technologies work in this schema.

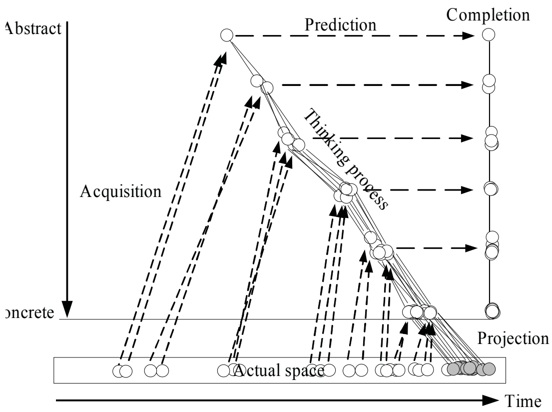
2. Pyramid Schema of Construction Information

In the initial stages of construction process, highly abstract information is first defined such as the concept and objective of construction. Then, information turns less abstract in the planning and design phases to more concrete information for projection into actual space. Although there are few studies about information schema in construction, Eastman (1999) represented design information as a cone with abstract and concrete information at the top and on the bottom surface, respectively. In this study, pyramid-schema design information is assumed (Figure 1 (a)).

Information is produced while obtaining various types of external information including actual space information, and abstract information is related to concrete information in the pyramid schema. In this paper, the pyramid conceptually represents a schema expanding downward from the top regardless of the shape of its base.



(a) Abstract-Concrete



(b) Relation to time

Fig. 1: Pyramid schema of construction information

The relationship between the pyramid schema and time is considered here. Figure 1 (b) shows the relationship between the pyramid schema and time by reproducing Figure 1 (a) as seen from the side. Information is related to each other in the thinking and projection processes in the design and construction phases, respectively. In these processes, information is produced while information in actual space is being obtained. The time efficiency of construction process is represented by the inclination of the entire pyramid.

Abstract information becomes concrete over a few to decades of years although the period varies according to the type and scale of the infrastructure. The natural and social environments around the schema vary during the period and information varies accordingly. Information variations may cause the information pyramid schema to collapse. Continuity from abstract to concrete information should be ensured in the construction process of a schema.

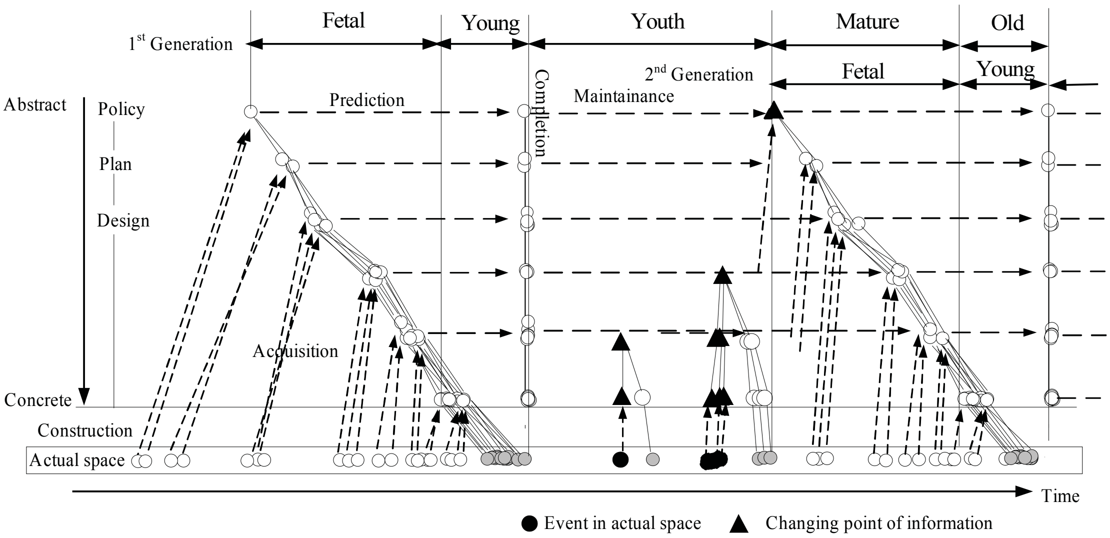


Fig. 2: Relationship between Infrastructure lifecycle and information schema

3. Consideration of the Spatiotemporal Schema of Infrastructure Information

As the most abstract information in the pyramid scheme, "policy" is positioned (see Figure 2). The process from abstract to concrete in the information space corresponds to the process of thinking from policy to plan, design and construction plan. Finally, information is projected from information space into actual space, or the schema is constructed. At the completion of a series of structures planned in accordance with a policy, the functions designated in planning as objectives are provided. Then, the infrastructures enter the maintenance phase. Information on structures in actual space obtained by using sensors or conducting inspections alters information in information space. Rebuilding the information schema is required below the point of change at the highest level. The results are projected again into actual space. In planned maintenance, the point of information alteration is determined as planned. The point of information alteration is corrected based on the information obtained in actual space by monitoring. When the point is actually reached, the information schema is rebuilt as planned and information is projected into actual space. The process of rebuilding the information schema and projecting information is equivalent to the repair of an infrastructure. The more abstract at the point of information alteration, the greater the scale of repair. This suggests that a life cycle exists for each level of abstractness.

If the policy at the highest level remains unchanged, the infrastructure sustains while the information schemas at lower levels are repeatedly rebuilt. No information at the highest level, however, remains unchanged. Social and environmental changes also cause the policy to vary. The variation demands rebuilding the entire information pyramid. Then, information is projected into actual space and next-generation infrastructure s replace the present ones. The cycle is divided into five periods as shown in Figure 2 and may be represented as described below by regarding structures as organic forms like W. M. Davis(1899)'s geographical cycle similar to the life cycle of organism.

(I) Fetal period: Period of planning and design of an infrastructure from policy development in the initial stages to the start of information projection into actual space (birth).

(II) Young age: Period of construction of an infrastructure until the end of projection of information obtained in information space into actual space.

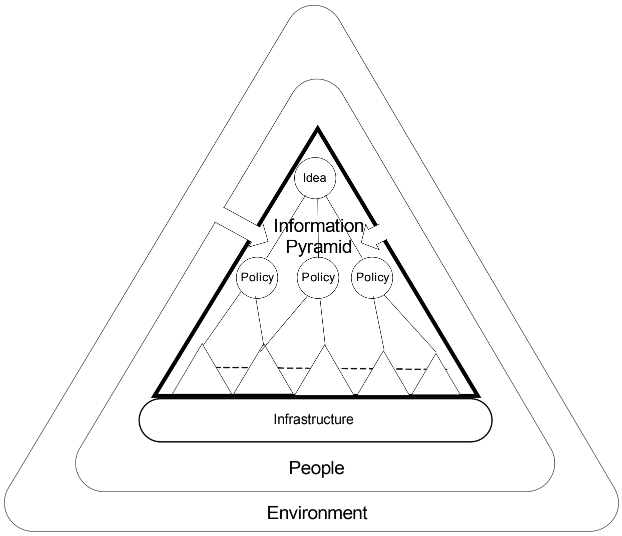


Fig. 3: Big pyramid information structure for infrastructure

(III) Youth: Period between the completion of projection of information into actual space and the alteration of information at the highest level. The infrastructure functionally meets social requirements. The structure is mainly operated and maintained in this period.

(IV) Mature age: While maintaining the infrastructure in actual space, information is built for planning a next-generation structure using the information on the existing structure.

(V) Old age: The young age of a next-generation structure is started and the structure is gradually replacing the existing structure.

No policy is related to a (or part of a) infrastructure on a one-on-one basis. Multiple structures are interrelated to one another and meet their functional requirements. In this study, policy is positioned as information at the highest level. Policy is, however, also hierarchically structured. Highly abstract infrastructure ideas exist at levels higher than policy such as "beautiful land", "safe and secure life" and "building affluent society". These ideas at the top of the information pyramid are divided into various ideas and policies that affect one another. Information pyramids are formed below the divided ideas. Materialized structures coordinate with one another and collectively constitute a big pyramid to put the ideas at the top into effect. The big pyramid is referred to as the infrastructure-information pyramid (Figure 3).

Information alteration at levels of more abstract ideas is expected to have greater impact on structures at lower levels. Information alteration of certain scale at lower levels attributable to environmental or social changes such as deterioration and disasters propagate to the upper levels of the pyramid and information is rebuilt accordingly. Thus, ideas and actual space maintain the schema of the pyramid as time passes in information space while supplementing each other, to prevent the pyramid from collapsing. the structures are configured in actual space based on the infrastructure information pyramid. The infrastructure information pyramid interacts with people who are involved in the pyramid as users, residents, and members of a country and of the earth. The pyramid constitutes a holistic body together with the natural environment, region and climate. Design engineers see the world composed of information through a small window.

Finally, the relationship between the infrastructure-information pyramid and information technology is discussed. Figure 4 shows the relationship between a model obtained by simplifying Figure 2 and information technology. Information technology here is divided into "acquisition", "expression and processing", "prediction", "projection (construction)", "life management", "operation", "information exchange with people and society" and "information management". These components are not fully independent of one another but coordinate with one another to create a more refined system".

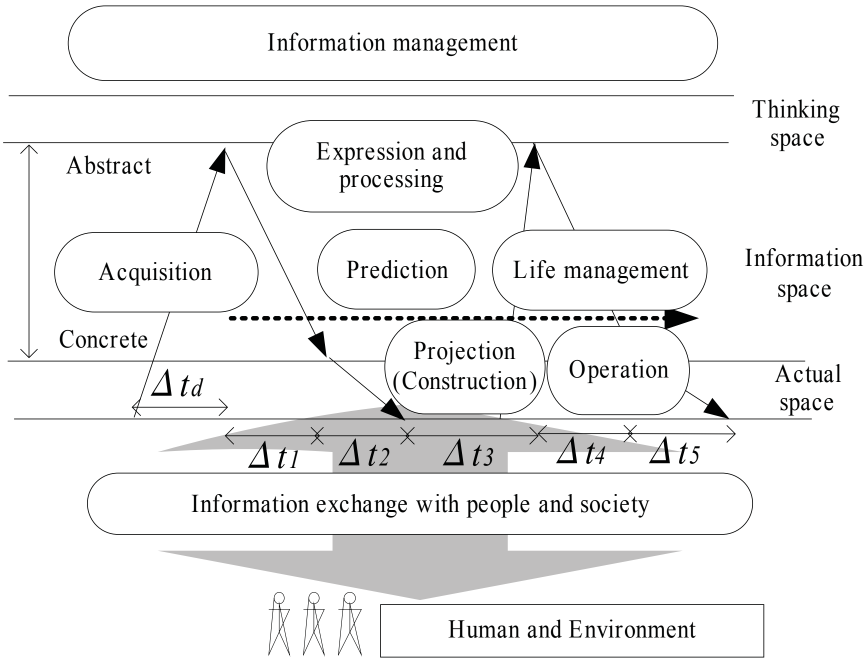


Fig. 4: Infrastructure lifecycles and information technology

Applying information technology eliminates delayed provision of information (Δt_d), reduces planning and design period Δt_1 (fetal period) and construction period Δt_2 (young age) and improves the efficiency of the construction process. Life management system, which uses high-level prediction technology in cooperation with monitoring technology is considered to increase the service life of the structure (prolong the youth Δt_3). Operation technologies are expected to provide services to users and increase facilities operation efficiency. Enhancing technologies for expressing and processing information, predicting and exchanging information with people and society is expected to contribute to better quality of infrastructures.

Gaining importance in the future will be "information management" for holistically capture and manage information. As shown in the life spiral model of information, the volume of information increases throughout life cycle. At stake is how to use the increasing volume of information for next-generation structures. What should be done will be developing a holistic information system and establishing a framework for describing information (information model), managing a large-scale information database built using the framework and extracting knowledge and wisdom from voluminous data accumulated as an applied technology.

Information technologies make various contributions to the infrastructure information pyramid but are also vulnerable as they are based on digital information. Mitchell (2003) presented various case studies and pointed out problems with network infrastructure. When holistically digitizing data on a large scale, the vulnerability of information systems dependent on information networks should be fully recognized, and methods for establishing robust and appropriate information systems as public social infrastructure and information management methods should be considered in preparation for an emergency.

4. How VR/AR Technologies Work in Information Process

VR and AR are utilized as the technologies for visualization and interaction in many areas in construction projects. Also, the information technologies related to the infrastructure lifecycles in Figure 4 contain these technologies. Added to these technologies, this chapter discusses the possibility of applying VR/AR technologies to visualize the pyramid information structure in this paper.

1) Visualization and evaluation of designed objects in virtual spaces
Information structures are not considered their readability for humans. In order to understand and manage the information structures, the advanced visualization technology should be applied. The information structures are able to be displayed in various views such as two dimensional plans, three dimensional perspectives and documents. However, the windows on displays are too small to visualize information structures in cyberspace. VR and AR technologies are utilizing for visualization of virtual objects in recent years. Figure 5 shows the relationship between information structures and those technologies for visualization. VR helps to visualize the information structures without any restrictions on viewing angle of windows. The advantage of VR in construction is that the scale in virtual space is flexible, for example, a human can be existed as a real-size human, or as a giant in the virtual space. AR which enables to superimpose information on the real spaces will be helps to recognize the virtual images in construction more strongly.
As the information structure shows the evolution of information processing within time axis, the four dimensional visualization technologies which can display the design materials in the real spaces should be required. Especially in the design stages, the level of accuracy and granularity of information will be gained with the advancement of design process. It will be a main subject how to visualize, evaluate and manage the information structures with this advancement using VR/AR technologies.

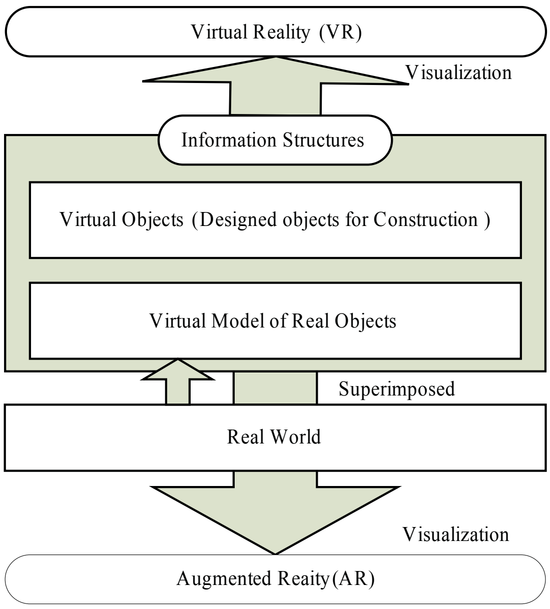


Fig. 5: Relationship between Information Structures and VR/AR technologies

2) Visualization of information structures
As the pyramid model of information structure proposed in this paper shows the relations of information items against time axis, the instances of these models will have more complex structures at the final stage. The virtual reality using stereoscopic technologies will help to understand the complex model which is unfolded in the three dimensional information spaces.

5. Conclusions

This paper sought the spatiotemporal position of information based on the present condition and problems of information technology in an attempt to identify the significance and role of information in infrastructure lifecycles, and discussed the concept of information pyramid composed of abstract to concrete information. The conclusions of this paper are described below.

1) The schema of infrastructure-information can be expressed using abstract-to-concrete information pyramid. The life cycle of information can be divided into five periods: fetal period, young age, youth, maturity and old age.

2) In the infrastructure-information pyramid, ideas are placed at the top and are related to specific infrastructures below via policies and other parameters. The big pyramid constitutes a holistic body together with people, region, climate and natural environment.

3) Information technology is divided into "acquisition", "expression and processing", "prediction", "projection (construction)", "life management", "operation", "information exchange with people and society" and "information management" corresponding to the spatiotemporal schema of information. These components eliminate delays in information provision, increase the efficiency of construction process and enhance the quality of buildings.

4) VR/AR technologies will help to understand the complex model which is unfolded in the three dimensional information spaces. Also it will be a main subject how to visualize, evaluate and manage information structures using these technologies.

In order to help develop infrastructure-information technology, developing a system of information schema and academically elaborating the system are necessary. Although this paper shows only the conceptual model of information schema, the case study and evaluation should be required in the next stage.

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CONSTRUCTION AIDS: AUGMENTED INFORMATION DELIVERY

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ABSTRACT: *This paper investigates the potential delivery of design information to construction sites through smartphones and tablet computing devices. There continues to be an increase in the complexity of Building Information Models (BIMs), which are capable of representing a variety of building aspects. This can encompass physical models, construction models as well as thermal and energy models. Despite the wide spread adoption of computing by architectural, engineering and construction (AEC) industries over the last thirty years, and notable attempts to deliver information digitally (Fu et al. 2006), this sophisticated data continues to be abstracted to paper drawings for information transfer. In this paper we review test cases in data delivery that appropriate the 'good enough' methodology found in contemporary computing culture. Augmented Reality (AR) tools are used as a vehicle to deliver information, which provides insights into the resistances and opportunities that AR and mobile computing might present within design and construction. In this project we adopt the 'good enough doctrine' that resonates with contemporary digital media. Using AR techniques (GPS, LLC tags, markers etc.) we rethink the delivery of information direct to location through smartphones and handheld tablets. Our project chooses not to replicate sophisticated BIM functionality such as collision detection, 4D time management or programmatic interrelations that has been explored elsewhere, for example in Plume and Mitchell's A Multi-Disciplinary Design Studio using a Shared IFC Building Model (2005). Rather, following suppositions from the 'good enough' phenomenon, it potentially supports the provision of 'good enough' information to a critical mass of participants. It interrogates notions of information densification and localised delivery, which are shifting the contemporary landscape of consumer computing. Finally it presents observational evidence that points to opportunities and resistance that AR may offer within design and construction.*

KEYWORDS: *Augmented Reality, Smartphones, Mobile computing, Communication, Construction, Design, BIM.*

1. Introduction

The increasing complexity of computing hardware and software within the AEC industry can be viewed as diverging from current trends in consumer computing. The computing power of devices such as the Apple iPad or Google Android powered gadget is modest when compared to a CAD workstation. iPads and iPhones deploy single applications that have limited functionality, which leaves both the device and application very easy to use. A device can hold hundreds of such applications, each tailored to a particular function and easily accessed through the iTunes store or Android Marketplace. Applications typically cost $2-40 rather than the $2000-4000 of popular CAD software. The increased sophistication of AEC software also opposes what WIRED magazine recently called the 'good enough revolution' (Capps 2009); where cheap and accessible services and devices are proving better at mobilising people than their complex counterparts. For example, until they were recently made redundant by smartphones, point and shoot digital video cameras like CISCO's 'flip' were outselling feature rich professional or semi-professional video cameras. We extend this critique to software such as SketchUp and Google Earth, which are perhaps emblematic of this phenomenon in design and construction. Although SketchUp and the 'flip' come under criticism for lacking sophistication they are 'good enough' for most purposes and mobilise a critical mass of participation and content. Notably this critical mass is having effects on consumer computing; innovative new applications made through 'mashing' simple services together continues to gather momentum in the contemporary digital landscape. Such innovation can be found in design (McMeel 2010), although it is hindered where software, services and applications continue to be overtly complicated. We speculate that the high level of specialised operational knowledge that CAD software like Revit requires inhibits mobilisation of a critical mass of participation within construction and thus potentially hinders innovation and problem-solving.

Our theme of consolidation is inspired by the writings of Deleuze and Guattari (2004, pp.361-364). By drawing on examples where a biological organism's metamorphosis is triggered by a critical mass of organic material they theorize densification is essential in generating newness. Into this mix we introduce the work of architectural theorist Richard Coyne and the philosopher Andy Clark. Clark has advanced the radical proposition that thought is spatial (Clark 2001), and Coyne hypothesises that virtualized environments can hinder cognitive activity. This critical grounding provides a point of departure for our discourse on AR within design and construction environments.

Elsewhere the authors are exploring the phenomenon of information densification in construction (McMeel and Amor 2011). Evidence suggests the noise and furor that accompanies on-site communication can be couched in terms of Deleuze and Guattari's themes of densification and newness, inasmuch as they serve to catalyse problem solving and reveal new opportunities. In *Difference and Repetition* Deleuze (Deleuze 2004, p.144) expounds the benefits of cross-communication between heterogeneous systems, suggesting, "something passes between the borders, events explode, phenomena flash, like thunder and lightening." We speculate that low cost and easy to use smartphones contribute to the cross-communication of highly specialised discipline-based systems of construction, thus have the potential to spark "spatio-temporal dynamicism" and enhance problem solving and collaboration in the design and construction environment.

2. Design and Construction Spaces

In this section we expand on Deleuze and Guattari's conception of space in terms of the striated and the smooth as a framework for conceiving of design and construction. There is evidence to suggest design and construction are not separate procedures (McMeel 2009), although design operations may be see as declining during construction they do not cease. We hypothesize that design and construction operate in two predominantly disparate spaces, the striated and the smooth. Deleuze and Guattari use a variety of models such as 'maritime' or 'technological' to articulate the levels on which these spaces operate. We will focus on their 'nomadic' model of striated and smooth space as a useful metaphor to conceive of design and construction.

2.1 A typography of space

In Deleuze and Guatarri's models of space the 'striated' is recurrently identified through repetition. This could be repetition through rhythm (musical model) or through horizontal or vertical lines (mathematical model). Their description resonates with what we will call 'design space;' the CAD and BIM (building information models) environments we are increasingly finding design operating within. These measured and exacting environments operate on notions of precision; they cannot as yet operate with fuzzy or approximate data. BIM software both requires and promotes the affordances of striated space (Fig. 1), a space that demands measurement, demarcation and precision.

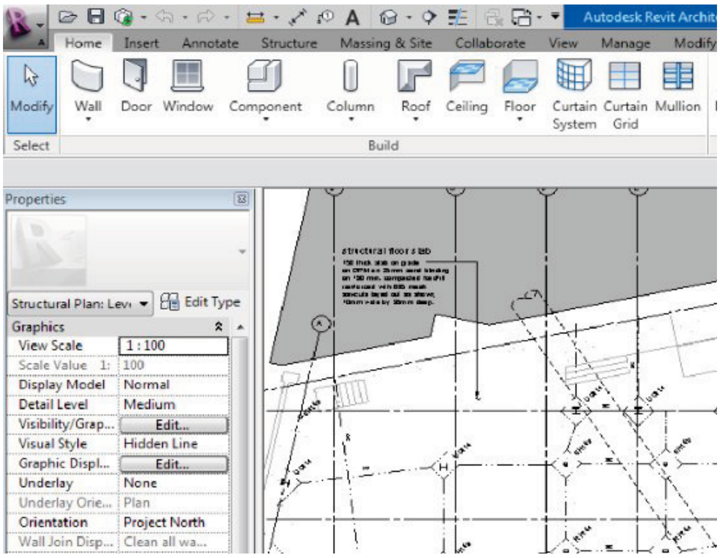

Fig. 1: The 'striated' space of the Autodesk design software Revit.

The measurement and demarcation that defines striated space is not identifiable in smooth space. When referring to smooth space Deleuze and Guattari use the word haptic; it is tangible and corporeal though lacks precise delineations. This resonates with the noise of the construction site, take for example the location shown below (Fig. 2) which awaits a staircase installation. Although staircase markings can be identified, closer inspection reveals evidence of change, revision, and movement. In this particular instance a beam affecting the staircase was only accurately located after work began; this impacted on the available head height and affected the 'going; and 'rise' of the staircase. As the consequences of these changes became apparent the marking and prospective staircase changed to ensure continued conformance to regulations.

Fig. 2: A 'smooth' space on a construction site awaiting a staircase.

Deleuze and Guattari lay claim to the notion that these two spatial conditions are never mutually exclusive, they always exist simultaneously in a state of constant flux and tension. Although Fig. 1 and Fig. 2 present observational evidence the metaphor resonates with contemporary construction, it nevertheless challenges much of the contemporary work on negotiating relationships within design and construction. Some initiatives suggest a more comprehensive mode of documentation (Roy et al. 2005) that not only conveys physical assemblies and relationships but also contains some instruction from the designer on the 'craft' of making. Others are attempting to 'lock-in' design through more rigorous processes that will reduce subsequent design changes during construction (Kagioglou et al. 2000). We theorize that Deleuze and Guattari's spatial metaphor is perhaps a useful lens for viewing design and construction. A designer, for example, is never totally removed from construction, they imagine the final building, a component, staircase or intricate assembly of a detail. The builder uses the idealized and abstracted drawings of the designer; a measured and precise representation of place that requires a cognitive leap to negotiate the relationship between the striated abstracted drawing with the physical limits of the actual staircase location. This framework of co-existence is useful within the context of design and construction because arguably very few agents and technologies operate between the two spaces. Cushman (2003) reports that knowledge exchange across disciplines can improve subsequent construction processes, however it is noted that often these knowledge exchanges happen at the end of a construction process.

2.2 Tools of the trade

The tools of design and construction are specialized and have evolved to serve particular needs. Hammers, spirit levels and saws have evolved to serve the needs of the tradesmen; pens, pencils and paper have been tweaked and tuned to serve the specific needs of design professionals. Even the pointed and precise pencil of an architect is quantitatively different from the chunky and robust pencil of a carpenter. Increasingly CAD and BIM are becoming ubiquitous, employed by architects, engineers and consultants who ultimately translate and manipulate designs within these software environments. The computation and simulation that occurs in design space is ultimately stripped away and converted to abstracted drawings (Fig. 3) that have changed little in the last two hundred years. Even with the proliferation of computing technology in the last fifty years and the widespread adoption of computers by the AEC industry in the last thirty years, the ontology of communication between disciplines and across the design and construction space has changed little in the same period.

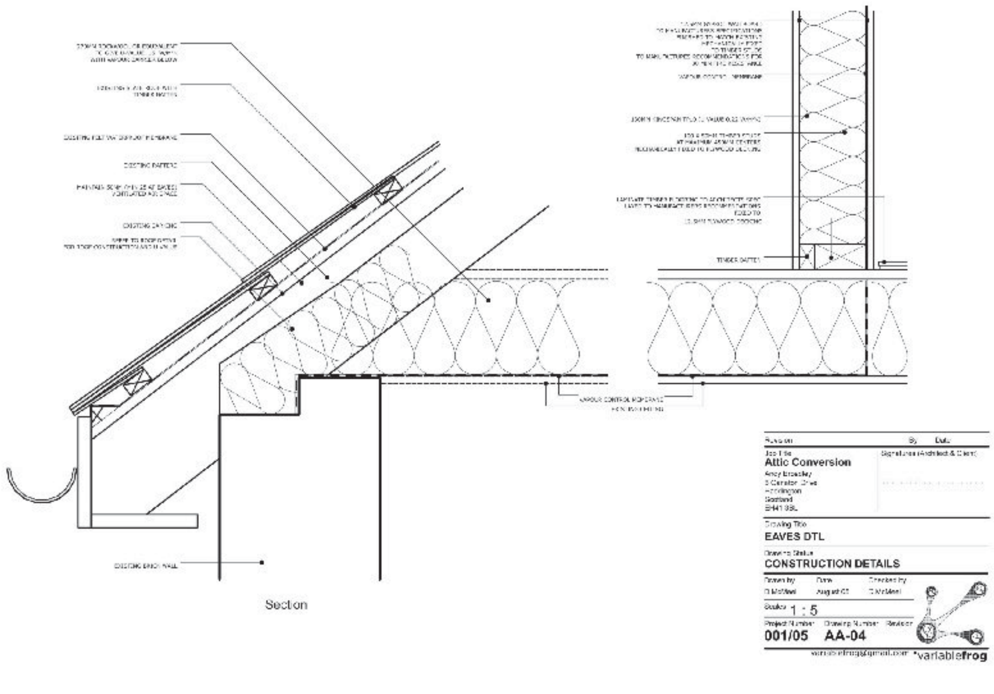

Fig. 3: A drawing for communicating a design intent.

Arguably, with the increased fragmentation of the construction process, the site meeting has added relevance. As tradesmen and sub-contractors are employed for a small fragment of time for a small fragment of work, the site meeting is perhaps the only occasion where designers, contractors and sub-contractors are in the same place at the same time. Although they may be unwieldy, long and occasionally fractious they serve as an important mechanism creating a feedback process between the two spaces. As construction evolves so to the design evolves, and like any substantial moving mass– be it physical or informational– repositioning releases energy, potentially causing breakages and creating tensions. In any building project these shifts and changes are ameliorated by design revisions, adjustments and alterations within the construction programme.

Increasingly, mobile phones are becoming implicated in the amelioration of change during construction (McMeel 2007), and previous work by McMeel suggests text messaging and mobile phone calling has a considerable affect on the relationship between design and construction space (McMeel 2009). Smartphones and tablet computing now offer increased potential for delivery, communication and representation of design and construction information through handheld devices. Within digital media, mobilising a critical mass of participation is key in effecting change (Polovina et al. 2004, McGonigal 2011). CAD and BIM continue to be available only to small numbers and communication continues to be via paper-based documentation, while mobile phones are available to a wide range of people within construction and provide access to a raft of potentially compelling technologies such as QR codes, GPS and Augmented Reality.

3. Test Cases in Augmented Reality

Over the course of a twelve-week project, a group of design students at the University of Auckland were challenged to explore AR within the context of both the design and occupancy of place. While this program is contained within the architecture course, the class is specifically concerned with exploring new and emerging media for the design and use of space. Our intention was simply for students to explore AR using their individual creative processes or spatial/technological requirements for driving their ideas. The organisers had at their disposal two Google Android powered Samsung Galaxy Tabs and one iPhone 4. These were available to the students enrolled on the course and could be 'check-out.' All of these devices are capable of running several free AR applications; although it transpired that a high number of students had access to iPhones or iPads and a strong sense of collegiality meant there was a lot of resource sharing by individuals fortunate enough to own one.

The design students enrolled in this course do not take mandatory coding lessons, although having used software such as Second Life and Rhino they are not unfamiliar with computer languages and coding. It is recognised that overcoming technical problems would form a portion of the course, however the intention was to maintain a critical focus on the design intent through this problem solving. Preliminary research into available AR applications found junaio (www.junaio.com) to be the most suitable in this case. Junaio provides good documentation and results could be achieved with a small amount of coding knowledge in the form of basic XML and free online storage space. Two basic types of AR are available within junaio, objects such as 3D models, and images and videos can be attached to locations or they can be attached to images. Junaio is working towards image recognition rather than using geometric markers that other AR toolkits are employing, this was also an attractive capability within the context of a design course. We explored alternatives such as Layar however it required knowledge of MySQL databases and requires the download and installation of proprietary software for locating and converting files for inclusion within the Layar framework. Junaio provides tutorial examples, files of basic code snippets and simple models that enabled a novice to 'copy and paste' code to obtain a basic working system. The junaio Google group forum also provided direction to free online web services (http://www.000webhost.com/) that work with the junaio API. Together these resources, along with some step-by-step tutorials and workshops under the guidance of the organisers, facilitated students without any particularly high level of programming knowledge to get an AR point of interest (POI) working and viewable on a junaio channel quickly.

Essentially there are three components within the junaio AR ecosystem, a smartphone running the junaio AR application, a content server and finally the junaio application management (JAM) server hosted by junaio. The JAM server takes requests from the junaio application running on a smartphone, obtains the relevant data from the content server and pushes it out to the junaio application. The content server is not hosted by junaio it is a standard php server that must adhere to certain communication protocols; students used the free web services mentioned previously, which proved to be reasonably reliable. Junaio has parsing and checking protocols in place but essentially the JAM server takes the data from the content server and pushes it out to the junaio application. Understanding this workflow was key and students were talked through it very slowly and then step-by-step they were introduced to setting up each of the three individual components of the ecosystem. They were also introduced to some 'best practice' document management for working with remote files. However, best practice workflow is not always the quickest and several individuals developed quicker working methods that ultimately resulted in loss of work.

The intent of the project was to focus on use-case scenarios for the communication and interaction with design documentation. In the following sections we will discuss and analyse several projects that emerged from the AR workshop.

3.1 Cross-faculty communication

In *Difference and Repetition* Deleuze discusses how different systems evolve unique "in-itself" ways of operating. This has been explored ontologically by Lee (Lee and McMeel 2007) within the context of design and construction. Deleuze goes on to explain the potential for dynamic newness, emergence and opportunities that become manifest during cross-faculty communication (Deleuze 2004, p.144); however the problems of this type of communication are also exposed to scrutiny:

"The transcendental operation of the faculties is a properly paradoxical operation, opposed to their exercise under the rule of a common sense. In consequence the harmony between the faculties can only appear in the form of a *discordant harmony,* since each communicates to the other only the violence which confronts it with its own difference and its divergence from the others." (Deleuze 2004, p.183)

In this respect the construction site offers both communicative opportunity and challenges for AR. There are a number of factors that restrict cross-disciplinary communication within design and construction. The availably and identification of information at the point of activity (POA) on site is cited as key to improved problem-solving (Peansupap and Walker 2005), yet drawings are primarily generalised and fragmented abstractions. General arrangement (GA) drawings lack assembly detail, assembly detail (AA) drawings lack aesthetic considerations and aesthetic renderings lack– although they might imply– either of the aforementioned. Furthermore, scale and temporality play a part; GA drawings are typically A1 (841 x 594mm) or A0 (1189 x 841mm) and often dominate the early construction programme. AA drawings are A3 (420 x 297mm) or A4 (297 x 210mm) and have more relevance in the later stages of construction; renderings– arguably the most relevant for conveying design intent– don't generally play a part in construction documentation. Compounding these factors, various stakeholders such as architects, engineers and interior designers all have different documentation. Each specialist has a unique perspective and documentation of their contribution to the design and construction process.

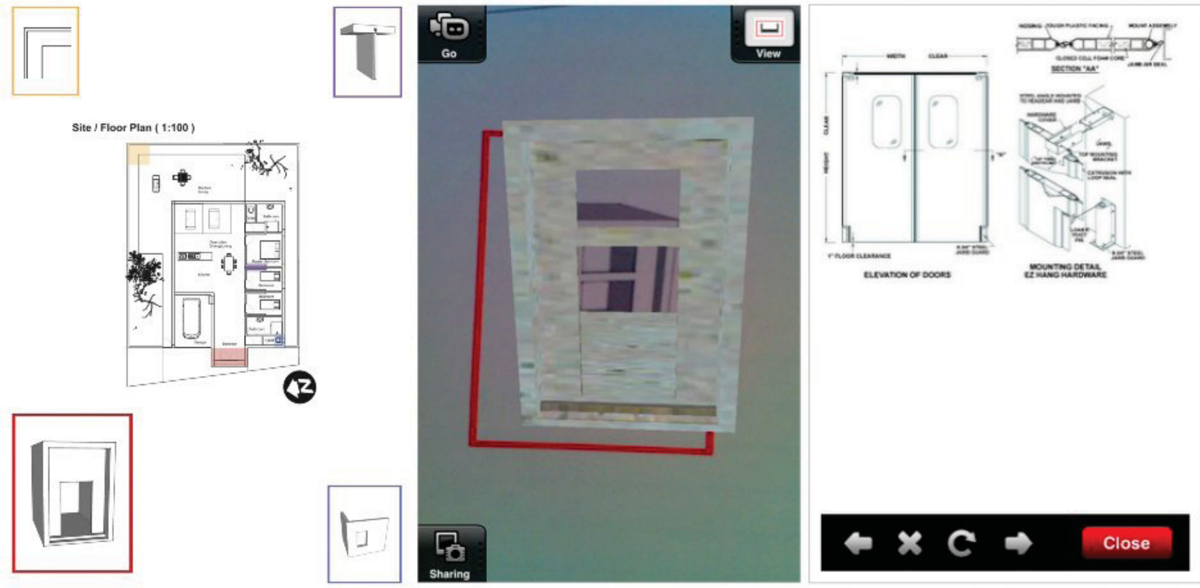

Fig. 1: Test case in using AR to cross a variety of communicative modalities – general arrangement drawing (left), AR model (centre) and assembly drawing (right). Project by Tommy Shin.

The following test case explores how AR can potentially cut through various modalities of documentation and provide multifaceted exposure to information specific to a particular site location.

This project by Tommy Shin seeks to enhance design communication to a multi-disciplinary group using AR. When review panels within a School of Architecture critique design the discussion can quickly shift from conceptual or aesthetic considerations to an interrogation of the details of construction. Each stakeholder in the critique could demand a different type of information. This test case rethinks the traditional GA drawing (Fig. 4 – left image), using AR it becomes a tool providing immediate links to a variety of modes and layers of information. Typically, a GA drawing would have text references to redirect a viewer to particular component or assembly drawings. This example has substituted these text references for small 3D renderings– aesthetic references– to the pertinent details. Here Tommy provides aesthetic information and also draws on the image recognition capability of junaio to add another mode of communication. When these images are viewed through a particular junaio GLUE channel on a mobile phone, a 3D detailed model is 'glued' onto the image (Fig. 4 – centre image). Now as a viewer moves round the image they will move round the AR model glued onto it; thus enabling visualisation of the detail from any perspective. This does not preclude the image containing a traditional text reference that would enable someone to find the relevant component or assembly drawing. However junaio provides a 'link' facility for a recognised image; Tommy uses this to immediately 'link' to a detailed drawing that can be loaded onto the mobile phone (Fig. 4 – right image). This notion was advanced further by Tim deBeer who wanted to convey dynamic information. He draws on the animation capability within junaio to convey assembly information. CAD files were imported into the Blender modelling program for conversion into the required file type (md2) for junaio. Animation within this software was surprisingly technical and problematic for the designers. Though Tim's working prototype (Fig. 4) still manages to demonstrate a proof-of-concept showing assembly animations triggered by a recognised image.

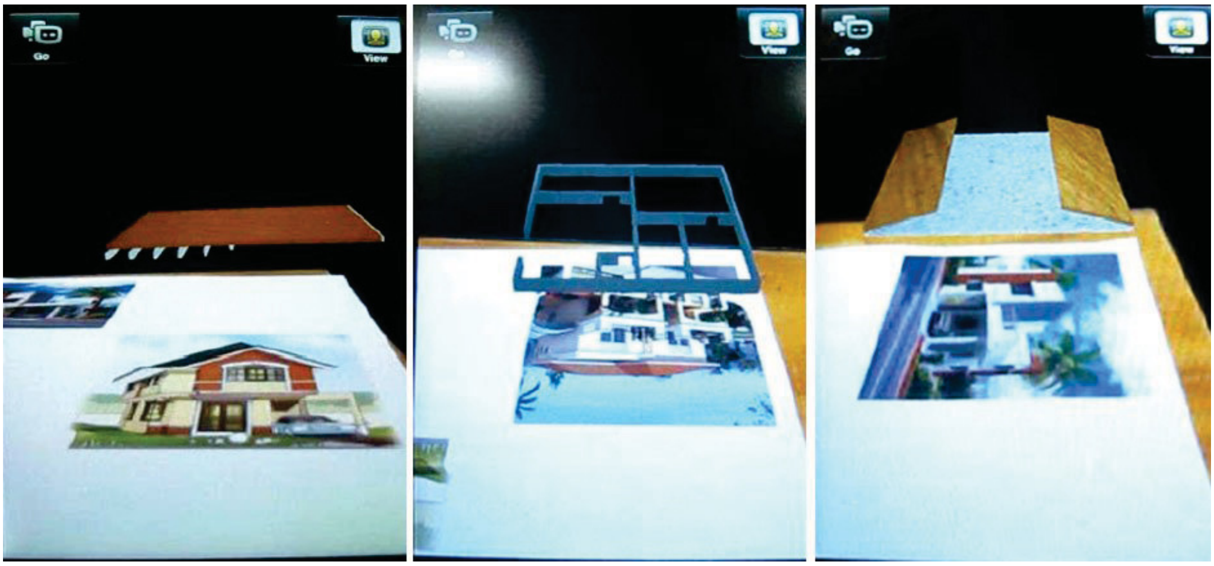

Fig. 5: Animation of different elements of a building viewed through the junaio mobile phone application. Project by Tim deBeer.

Returning to our theoretical grounding and Clark's suppositions regarding scaffolds, we might conceive of drawings as cognitive scaffolding for construction. Each type of drawing and discipline provides unique insights to different facets of a project; although for most of construction there is temporal, spatial or ontological distance between them. This project advances the drawing as technological scaffolding for cognition, it uses AR to augment the drawing and potentially reduce the distance between the different design and construction spaces within the building process; increasing the opportunity for cross-disciplinary communication.

4. Cognitive Scaffolding

In this section we will look at how AR might be used for the construction and exploration of a design process in spatial terms. According to Clark, human beings are adept at using technology for personal enhancement (Clark 2003). In fact he claims the extent to which human beings use technology to construct these cognitive scaffolds far surpasses any other species (Clark 2001, p.19). Invoking Hutchins (1995), Clark puts forward a particularly compelling example of a cricket (Clark 2001, pp.8-15). The mating ritual comprises of the male calling, the female recognising the male call, calculating from where it comes and then ambulating in the direction of the male. The dominant theories in cognitive science would suggest we have just described three distinct cognitive activities. Clark contests this notion and explains the cricket's ears are on its forelegs and open to the world at two points, a single sound reaches the ear through slightly different routes and slightly out of phase. This phase difference favours the male call, consequently it would appear that the male mating call is one of the few sounds that can be heard clearly through the female's aural scaffolding. Having ears located in the forelegs results in ambulation and rotation directly affecting the clarity and directionality of the sound and thus the prospective mate. Clark theorises what appears to be a complex three-stage linear cognitive process is in fact shaped into a single cognitive operation, with the help of the cricket's evolved biological 'scaffolding.' Clark goes on to single out human beings use of technology and design to enhance or increase the efficiency of thought as far surpassing any other species. Thus we contend that design; architecture and now augmented reality are implicated in supporting or hindering cognition.

Returning to the domain of architecture, we should perhaps acknowledge that historically buildings and public spaces served to do more than provide a utility of place. From hieroglyphics found on Egyptian Pyramids to elaborate friezes adorning Roman public buildings we find architecture serving to record and re-collect memory and collective experience. Perhaps Peter Zumthor serves as a contemporary example of the architect as creator of environmental scaffolding. In *Thinking Architecture* Zumthor (2006) explores the notion of architecture evoking memory. The sound of gravel underfoot can trigger a remembrance from an earlier experience; the feel or look of a door or handle can elicit a childhood memory of the need to pull or slam the door. Couching Zumthor's reflections within Clark's suppositions we propose that this is architecture as cognitive scaffolding. Zumthor approaches architecture with subtlety, he has added steam, sound, and light to his architectonic toolbox and creates architecture that has the sensuous and the experiential at their core. Zumthor is reported to have said of his Bath House at Vals:

"The meander, as we call it, is a designed negative space between the blocks, a space that connects everything as it flows throughout the entire building, creating a peacefully pulsating rhythm. Moving around this space means making discoveries. You are walking as if in the woods. Everyone there is looking for a path of their own." (O'Grady 2009)

These are designed as places of discovery, relaxation and stimulation. Rather than an individual configuring space for their own relaxation or writing process, here the architect designs to enhance a particular emotional and cognitive state. Complicating this for architects and designers is the current proliferation of augmentations to our intended reality. Freely available mobile phone applications like junaio, Layar, Aurasma and Wikitude to name but a few allow digital scaffolds and topologies to be overlaid on reality, we speculate this effects personal perceptions of architecture and place, consequently there is an impact on creative processes be they writing or design.

Fig. 6: Three views of informational AR scaffolding, viewed on a map (left), as a list (centre) or in a 'live' spatial view (right), which responds to panning, tilting and movements of the phone. Project by Rickey Gong Wang.

This test case uses AR as a metaphorical 'transporter' by using junaio's LLA markers. These markers contain latitude, longitude and altitude (LLA) information. Once recognised, the smartphone discards any current locative information in-lieu of the data contained in the marker. This functionality is intended for use indoors, where it is typically difficult to get an accurate location lock. However, Rickey appropriates this utility to literally transport the viewer to his design space. The designer is still making decisions regarding the content of his design space, we can see (Fig. 6 – centre image) notes on theory, design progress, concepts etc. Rather than representing an idea as an abstract concept, now a person or group of people can be transported into the design narrative (Fig. 6 – right image); design decisions can be viewed within the noise and furor of the creative process. Noise and furor, we have theorised elsewhere (McMeel et al. 2011) contributes to problem solving during construction.

5. Conclusions

Design and construction processes are comprised of temporally, spatially and conceptually distinct constituents. The first test case in this paper provides us with a glimpse of AR increasing the potential for accessing different types of documentation and representation of design. A drawing can now serve as a portal to disparate information that is location specific, increasing ease of access to different stakeholders drawings, documents or models of a building project. Here, we see the benefits from cross-disciplinary communication through BIM software being extended further into the construction process. Our test cases demonstrate how– with mobile devices– knowledge can be meaningfully placed in the hands of the skilled on-site specialist and facilitate a deeper knowledge exchange between the disparate design and construction disciplines. In our second test case a designer 'transports' us within the noise and furor of his design process. Informational noise that– we hypothesise– provides raw material to serve as a catalyst for Deleuze and Guatarri's consolidation of new creations and solutions. Although our test cases are admittedly modest in scope they emerged from a contemporary pedagogical design environment occupied by designers fluent with mobile phones and locative media. They present observational evidence of compelling starting points for reconsidering 'aids' for design and construction processes.

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4D GRID-BASED SIMULATION FRAMEWORK FOR FACILITATING WORKSPACE MANAGEMENT

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ABSTRACT: *The scheduling of Building construction includes a number of impact factors, which make it very complex, tedious and time consuming. This process includes the identification of different activities and the technological constraints between these activities. Then available resources have to be assigned to these activities to fulfill the project criteria time, cost and quality. Traditional methods of planning, such as 2D technologies including bar charts, network diagrams and other scheduling tools, which are typically methods for modeling the process of the project, still dominate the practice. These methods lack a representation of the attributes of the component installation and the spatial information. This leads to drawbacks during the execution of these tasks such as overlapping of work areas, reduction in productivity, safety hazards, long hauling paths and poor quality of work. This paper proposes a 4D grid simulation framework to address the dynamic nature of work space management. In addition, a simple building project is used as an example to demonstrate the applicability and feasibility of the grid-based simulation framework. This simulation framework executes only tasks which satisfy the requirement of the space availability. Considering this space concept valid, robust, and thorough, better work preparation, augmented by the proposed system, will improve work efficiency, eliminate conflicts on site and will finally contribute to robust construction schedules.*

KEYWORDS: *Workspace Management, Grid, 4D Visualization, Simulation, Optimization, Scheduling*

1. Introduction

Space is regarded as a limited resource on construction sites. As time elapse and work progress on site the requirements and the characteristics of work spaces (type, size, and work location), and the subsequent activities, which take place on those areas, change constantly in time and in three dimensions. So that it is not unusual for the parties involved not to compete on the available work spaces, potentially interfering with each another, or when the workspace of on-site personnel conflict with material stacking space. These kinds of activity space conflicts occur frequently, severely affecting the process and efficiency of construction and resulting in productivity loss [Wu and Chiu, 2010]. Furthermore, a spatial case study was conducted on a £6 million construction site at the University of Teesside signified that 30% of non-productive time on site due to the lack of detailed and space planning [Mallasi and Dawood, 2002]. Therewith, one of the main problems associated with construction operation on site is obviously the coordination and interaction of different trades and their requirements for multiple pieces of equipment, crew member, material, etc. for the foreseen schedule.

Since early the 90th the Center for Integrated Facility for Engineering (CIFE) in Stanford University has lead research projects in collaboration with construction industry related to 4D CAD and formalized the necessary construction knowledge to build 4D models. They have developed a methodology that guides project planners in generating 4D models from 3D product models. For instance, Collier and Fischer linked the temporal data to layers in a 3D CAD models through a commercial 4D simulation system called Construction Simulation Toolkit from Jacobus Technology, Inc. The output movie is shown in "Walkthru" [Collier and Fischer, 1996; Akinci and Fischer, 2000]. Their work has made rapid development in providing engineers with an effective tool to manage the coordination complexity of the site, especially in conveying the sequence of construction processes. Hsieh et al. state an increase recognition from the construction industry on the benefits of using the 4D technology for increased productivity, improved project coordination, and optimized on-site resources [Hsieh et al., 2006].

Significant work has been done on the work space modeling in the last decade. For instance, Akinci et al. formalize the general description of space requirement through a computer system. Their research efforts have advocated the use of space templates to represent the dimensional properties of work spaces. The development of the work space templates includes laborer space, equipment space, hazard space and protected space. By using 4D CAD, a user can automatically generate the project-specific work spaces according to schedule information and represent the work spaces in four dimensions with their relationships to construction methods [Akinci et al., 2002c]. Akinci et al. extended the concept of generated and assigned work space to construction tasks to include a 4D methodology to detect and analyze potential time-space conflicts [Akinci et al., 2002b]. Another approach proposed by Guo focuses on space availability due to time and scheduling. He integrates two typical tools, AutoCAD for space planning and Microsoft Project for scheduling to develop and represent the spatial planning in 2D. The user can define an occupancy structures in the CAD environment. By laying the layers over each other, spatial conflicts for a specific time can be detected. According to criteria such as the size or percentage of the overlapping areas, the overlapping duration and their share of the processing time is attempted, by which the severity of the conflict can be determined. He has developed appropriate strategies for conflict resolution [Guo, 2002]. Akbas proposes a geometry-based process model (GPM) that uses geometric models to create and simulate workflows and work locations. This method provides spatial insight into the planning of work spaces and space buffers for repetitive crew activities [Akbas, 2004]. However, all these researches could not fully address the dynamic nature of work space requirements. The workspace was assigned to a task or a collection of tasks such as install windows in the east side of the building, which remained in this position for the entire duration. That is to say, work spaces assigned and only updated, when the horizon period of planning (one week, two weeks, etc.) is expired. Winch et al. advocate the use of a one-week planning duration when carrying out spatial planning for the execution level. They have developed a methodology, which allows construction planners to interactively "mark-up" areas in "AreaMan" for task execution. Tasks are assigned manually in MS project to these drawn areas. Lastly, the analysis of construction operations achieved through the development of the "SpaceMan", which allow users to identify the critical spaces and their relationship to the critical path. Furthermore, it can provide the user with suggestion to resolve time-space conflicts [Winch and North, 2006].

Therefore, we proposes a 4D grid-based simulation framework to overcome the shortcoming from previous research, which helps planners to organize the work space at the execution level of task prior to construction, to visualize the occupation level of the space model, and to update the occupation level of the space model within short notice. The paper is structured as follows: first we formalize the work space description as well as the data model for work space management. Next we describe the representation of work space and the proposed methodology to address the objective of this paper. Before we draw our conclusion and the future approaches, we demonstrate our concept in a simple case.

2. Work Space Formulation

Construction activities require a set of adequate workspaces to be executed in a safe and productive manner. The researches have been taken two distinctive attitudes to formalize work space requirements: zone generation and work space types. Zones have been used from different researchers to refer to the spaces or groups of spaces, which required by specific task to serve construction operation as working units. Shaked and Warszawski defined zone by their nature (horizontal and vertical), their designation, (basement, lobby, mechanical, office, elevator shaft etc.), and their location [Shaked and Warszawski, 1995]. Thabet and Beliveau have pioneered the research field of zone generation. They suggest to divide the floor into a number of zones and then broken down into work blocks. Resources (material, equipment, laborers, etc.) can then be allocated to these blocks [Thabet and Beliveau, 1994b]. Akbas proposes a geometry-based process model (GPM) uses two mechanisms for zone generation, namely *decomposition* and *aggregation*, to create and simulate workflows and work locations. On the other hand, recent researches on work space planning included this work based on their concept of the identification of the work space types approach by Riley et al. For instance, Riley in his theoretical proposal 4D model includes four types of work spaces, i.e. the physical work space; storage areas for materials; paths for materials; and access points for unloading materials onto building floors. He assumed that they are related to the production planning of multiple crews [Riley, 1998]. Furthermore, the research efforts from Akinci et al. have advocated the use of space templates to represent the dimensional properties of work spaces. The development of the work space templates includes laborer space, equipment space, hazard space and protected space. Using work space types provide project planners a flexible way to express the characteristics of configurations that are of interest of determining the work space requirements for individual trade as well as for different concurrent working trades. Therefore, this paper proposes the inclusion of the different types of work space required by a specific task that are based on the classification of the different types of spaces made by Bargstädt and Elmahdi [Bargstädt and Elmahdi, 2010]. In addition to the identification of work space types by Riley and Sanvido, we identify through site observations at different construction sites at the interior construction work a -*debris work space*-. Figure 1 illustrates the work space types we include in our model and how they interact with each other to perform a construction activity. We implement them in a simple case study specifically for trades at the interior construction work.

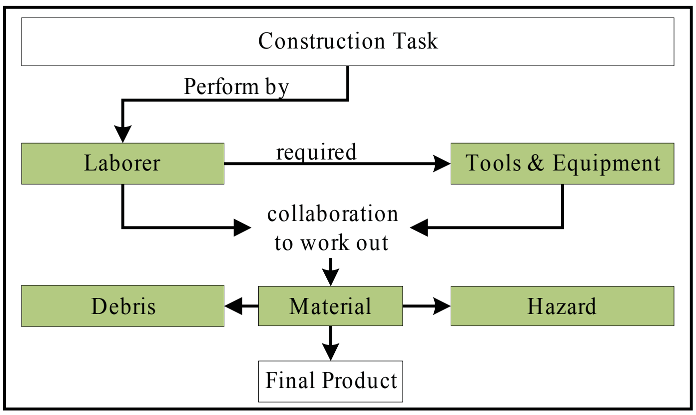

Figure 1: Formulation of work spaces

2.1 Data Model for Work Space Management

A clear structure of the database system with the 4D simulation framework is essential to couple different data types of data source and to serve a host of commercial users under different deployment environments. The data model for the work space management is a relational database schema, which mainly describes the relationships between the *Task* object (tasks with the schedule), the *3D Component* object (components within 3D model) and the *Work space* object (types of work spaces). Figure 2 illustrates the structure of the database and how they will bind together within the system framework. The *3D Component* object and the *Task* object are bound in *one-to-many relationships* through a unique ID (TaskID), where one or many tasks can act on one 3D component. This can lead to work space conflict, if two or more tasks have the same start date and act on the same object. There are two types of workspace are defined in this research. One is temporal workspace which is relating to time, workspace will be released when task is finished. Another on is fixed workspace, the specified workspace will be owned by building element forever. Thus the *Workspace* object regulates the relationship between the task object and 3D component. It identifies from one side the required workspace types for a specific task. On the other side the *Workspace* and the *3D component* relationship ascertain the availability of the required work space.

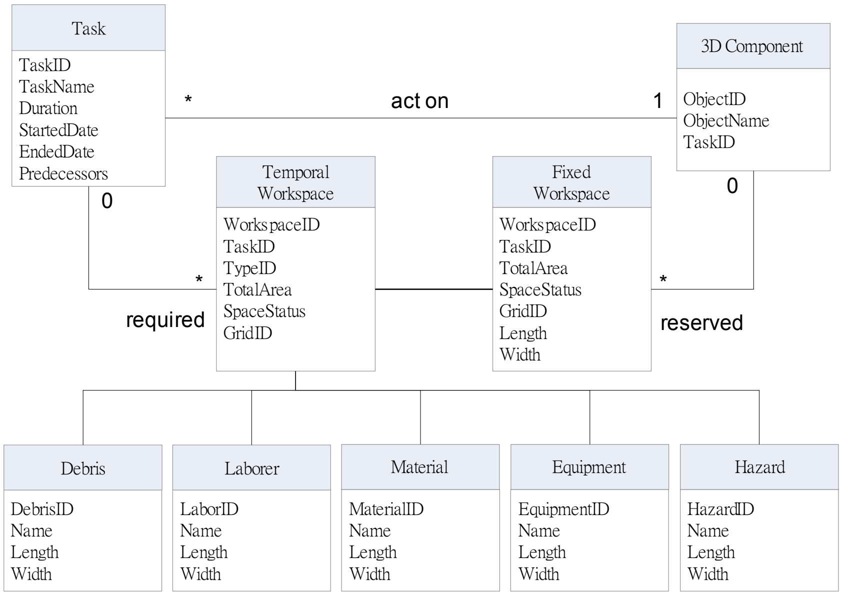

Figure 2: Relationship between workspace, 3D component and task

2.2 Representation for Work Spaces

Kamat et al. state that the representation of construction operations depends on the level of detail and realism, and on the information required to be captured from the process [Kamat and Martinez, 2000]. They classify visualization into four groups: schematic 2D animation, 3D animation and 4D CAD visualization. Commercial 2D and 3D animation software have been used widely in manufacturing systems. But they are built based on process interaction on their simulation framework and so they are not effective for construction operation [Martinez and Ioannou, 1999] . Although, 4D CAD model support project planner in identifying and analyzing the bottlenecks of the project plan. However, 4 D CAD systems do not support visualization of construction operations that leads to the end product [Kamat and Martinez, 2001].

The literature in site layout planning provides valuable inspirations for explicit dynamic representations of space. For example, Hegazy and Elbeltagi have proposed a model to visually arrange required areas within a construction site [Hegazy and Elbeltagi, 1999]. This model represents any irregular user-defined construction site by dividing the site into two-dimensional grids. The size of the grid is determined as the greatest common divisor of all required areas. The required area can take on irregular shapes and is represented as multiple units of a grid, which are added up to make the required area. To define the position of any required area on the site, a location reference is formulated, which is used to define the starting position at which a required area is to be placed on the site. As well, non-orthogonal boundaries can be modeled using stepwise approximation. Later, Elbeltagi et al. improved this model to include health safety and productivity aspects with site layout analysis [Elbeltagi et al., 2004]. Another application is presented by Mawdesley et al. 2002. In their model, the positions and areas of all the facilities are shown in the form of grid units [Mawdesley et al., 2002]. AbouRizk and Mather have proposed a simulation concept for earthwork operations by connecting the simulation model with geometric models in external CAD software. The 3D CAD geometry is decomposed into a grid, where each grid element stores different information such as construction order, construction method, average depth, etc. [AbouRizk and Mather, 2000]. The advantages of a grid-based representation of required area are: a) it is feasible and easy to understand the occupation level of the site since space is graphically described; b) required area can be irregular or user defined shapes; and c) it increases the communication between model developers and users. Therefore, the 4D grid simulation framework implements the same concept to manage the available spaces, required spaces and the spaces in use (locked spaces) on production sites.

Many researchers advocate the need for 3D + t analysis of the work space [Koo and Fischer, 2000; Fischer and Kam, 2002; Akinci et al., 2002a]. Project planners wish to have the sense of the 3D space occupation, as well as the severity and the impacts of conflicts between two different trades and/or completed product overhangs, in order to decide upon the appropriate measurement on work processing. However, one of the current limitations of 4D graphic content is the level of granularity of 3D entities [McKinney and Fischer, 1997]. This limitation can be overcome by the proposed methodology in this paper. The occupation level of the model will be updated by the starting of a new event such as “task started” and/or by the ending an event such as “task finished”.

3. 4D Grid Bases Simulation Framework

3.1 Proposed Methodology

The procedure of the 4D grid simulation framework is a discrete event simulation framework. It outlines the search for a task that can be started for the current simulation time. Upon the occurrence of an event, all tasks do not start with the state to examine the performance of their technological constraints. Those tasks that meet their assigned constraints will be checked to verify their execution possibility to be started for the current simulation time. They are stored as the next executable tasks. The next executable tasks, which have satisfied their technological constraints are their status “not started” and has to be checked up on for the fulfillment of the spatial constraints.

The identification of required work space associated with a specific task achieved through automatically synchronization of all 3D components via ID keys, that is to say the ID of the task will match with the ID of the 3D component and then verified the work space requirements. After we identified the required work space associated with specific task, the spatial constraint component verifies the availability of the required work spaces for the current task in a hierarchical structure. That is, first material, equipment space are verified for their availability, and then the laborer work space is verified for their availability with the space requirements of the tasks already being executed. On this basis, an evaluation will be made to avoid the possible overlap of the activities of required work spaces. The required work space, or rather, the required number of grids has to be locked during its execution. That means these working spaces cannot be used by other work steps. After locking the required number of grids, the work step state changes from "task not started" to "task started". Subsequently, the set of "task not started" task is checked to see if the required space is available by going to step one until no more work steps can be started at the current time. The simulation time is continuously checked during a simulation run. If the required time has expired, the work step status changes from "task started" to "task finished." and is marked as finished. Its locked working spaces will be unlocked and can be used by other work steps. Figure 3 illustrates the procedure of the proposed methodology.

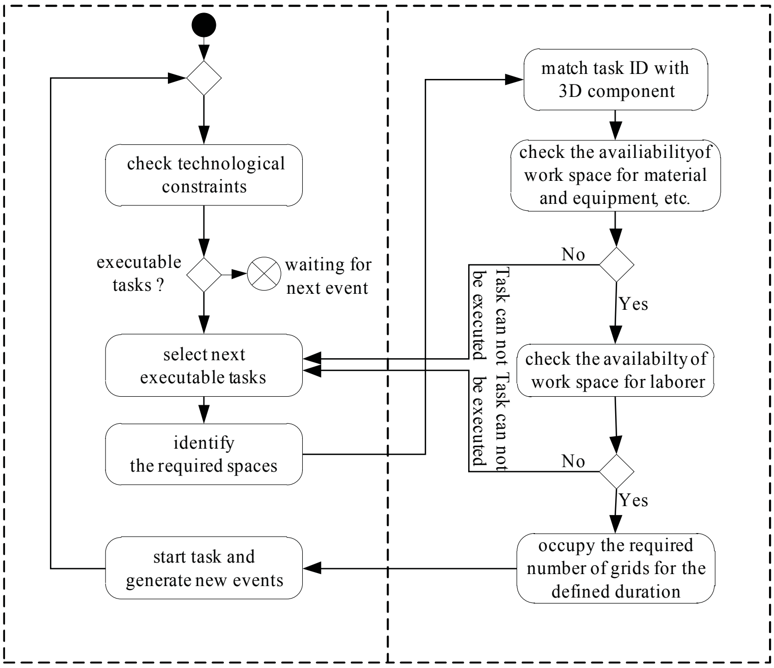

Figure 3: Procedure of the 4D Grid Simulation framework

3.2 System Framework

The implementation of the grid-based simulation framework was carried out in the MicroStation Visual Basic for Applications to acknowledge the work space requirements within the schedule. The system framework provides information platform that incorporate databases from different sources, that is data from different scheduling software such as MS Project, Primavera, etc., the 3D model from AutoCAD or BIM format and a built-in database for the different required work space types. Table 1 shows the color scheme implemented in this work. Figure 4 depicts the system framework, which include the following components to facilitate the dynamic nature of work space:

- Data Management: is responsible to store the work space data and manage the requirement of the availability and the requirement of the work spaces associated with specific task.
- Grid generation: allow the user to define the boundary of the working layout space i.e. site layout, floor layout. It also allows the user to specify the grid size or rather the number of grids in two directions across the plane of the layout. Thus two extra coordination will added to the points on the space layout namely the U-direction which is the direction in which the data points that defined each row were entered, and V-direction which is the direction in which the columns were defined.

- 4D Data Binding: is responsible to bind the different data of the system framework schedule, work space and the 3D component from the 3D model.
- Workspace Conflict Analysis: this component support project planner with analysis the different types of conflicts.
- 4D Visualization: this component is responsible for visualization the processes leading to the end product, the end product as well as the occupation level of work space as well as conflict in 4D (X, Y, Z + time). It also shows how space conflicts occur between two different trades.

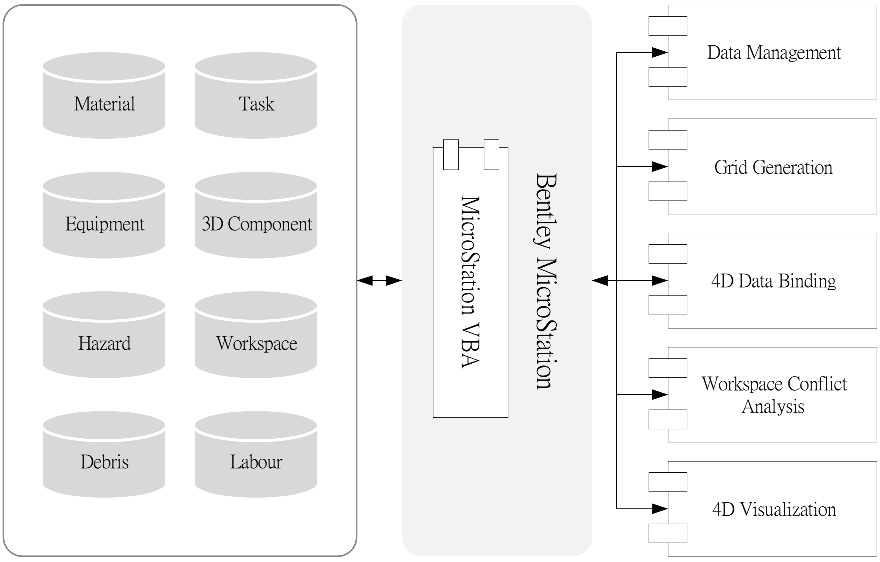

Figure 4: System Framework

Table 1: Color Schema

(green)	Free Workspace	(orange)	Equipment
(red)	Fixed Workspace	(yellow)	Hazard
(blue)	Laborer	(pink)	Debris
(purple)	Material		

4. Demonstration

The case study is a high rise building composed of 5 floors. Our investigation is concentrated at the production "Floor Level". Therefore, we limit our observation for one floor to demonstrate the applicability and feasibility of the grid-based simulation framework. The following five trades are modeled in the case study: plumbing as an example for the building services engineering trades, installation of interior doors and dry walls as an example of dry interior construction work, screed work and painting as an example for wet interior construction work. Figure 5 illustrates an overall representation of the implemented trades, representing the different objects. This simulation framework executes only tasks which satisfy the space requirements. The grid size is user defined according to the accuracy needed. The required work spaces are driven due to their installation positions, related work spaces (laborer, materials, equipment, debris, and hazard) and task dependencies so the impact of the interaction between the different trades and their work directions can be driven. We use different colors for the occupied number of grids for the different required work spaces by one trade (laborer, material, equipment, hazard and debris) as well as between different trades, thus we can clearly distinguish between the different concurrent working trades during the run of the simulation. For this purpose, we used different RGB values to generate a color corresponding to the individual trades.

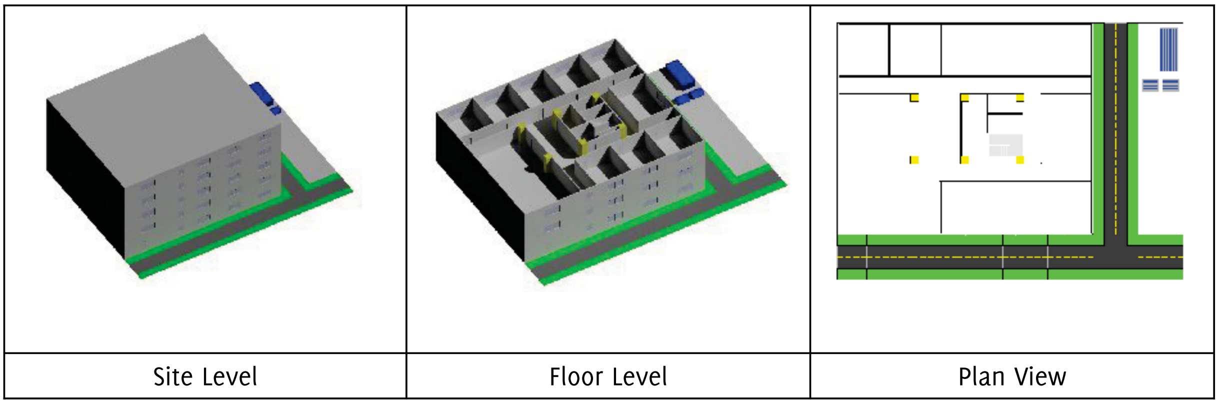

Fig. 5: A simple example

Figure 6 shows a snapshot from the one simulation run, which shows the occupation of the required number of grids for different trades with their specific work space requirements using different colors at specific time during the simulation experiment.

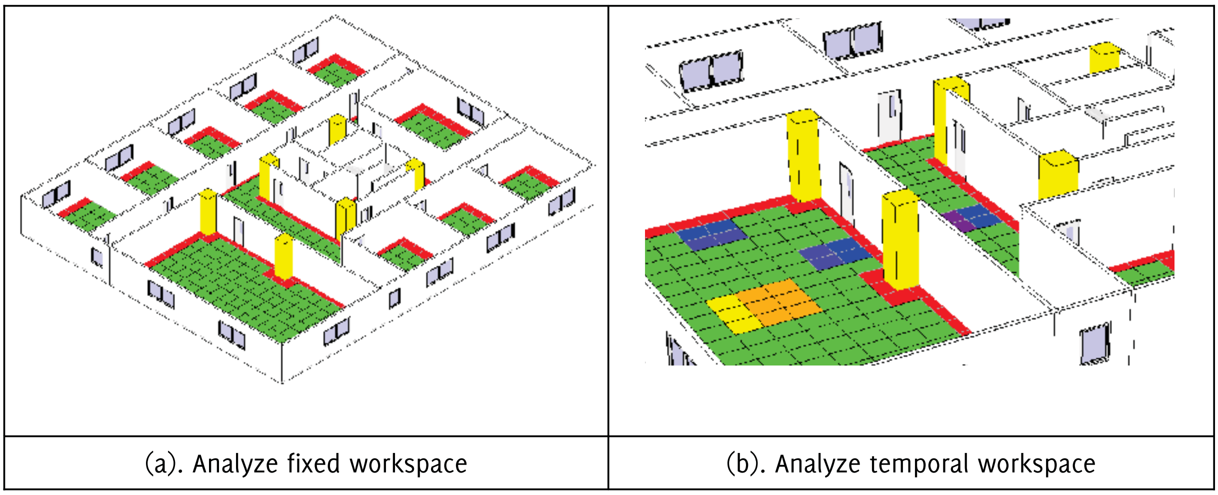

Fig. 6: A snapshot from the one simulation run.

5. Conclusions and Future Work

The goal of this paper was to develop a simulation approach, which acknowledges the spatial aspects within the scheduling of construction projects. That is, the required work spaces of various trades and their allocation. The integration between the existing scheduling of the construction process and the developed spatial aspect for space planning in has been successfully achieved. Recently, we have validated the concept in one prospective job site. The 4D grid simulation framework is general enough to accomplish the different requirements of individual as well as different trades. The occupation level of the floor was monitored using a 4D grid (3D +t). Furthermore, this tool can support industrial partners after providing the schedule input data as well as the spatial input data in evaluating the robust of their schedule for concurrently working trades at the production level. Thus, a project planner can investigate the work sequences for disturbances caused by cramped work areas and/or identify conflicts prior to construction.

Considering this space concept valid, robust, and thorough, better work preparation, augmented by the proposed system, will improve work efficiency, eliminate conflicts on site and will finally contribute to robust construction schedules. This is on-going research. Therefore, execution strategies for different tasks and the reduction of work productivity due to different factors such as limited work space availability will be developed in a future approach.

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EXPERIENCES ON DESIGNING USER INTERFACES FOR A TELE-OPERATED CRANE

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ABSTRACT: *This research focuses on the design of the user interface for a tele-operated crane. Its major challenge is to overcome visibility and lack of degree of reality in tele-operations. We would like to explore the possibility to integrate augmented reality (AR) technology in the interface, providing real-time warnings to prevent unsafe operations. We conducted two studies to validate this idea. The first study was to evaluate the technical feasibility. We set up a small-scaled simulation site and equipped four cameras. We then developed a user interface with multiple views, which linked with the cameras and augmented reality modules. From the implementation, we found that the system can be executed in the real-time and have high potential to be applied in actual erections. The second study focused on the interaction with the users. We invited 30 users to conduct the tests. Results show that the use of a tele-operated interface with multiple views setting reduces completion time by 10% compared to a conventional interface while performing simulated erection tasks. The integration of AR improves safety, the number of collisions was reduced by 57%. This solution is ideal for improving the safety and efficiency of remote erection tasks.*

KEYWORDS: *Augmented Reality, Path Planning, Attention-Based Design, Multiple Views.*

1. Introduction

Tele-operation technologies have been widely applied in diverse fields such as rescue missions, mining, and space exploration. During the last two decades, there has been much progress in the utilization of robotics and automation technologies in construction operations for further improving construction safety and productivity. A growing number of researchers have focused on studying the possibility of developing such intelligent and advanced construction equipment, and advanced robotics and automation technologies have been integrated into construction equipment in recent years. Golparvar-Fard et al. (2009) utilized augmented reality to monitor construction progress. Wang (2008) analyzed the applicability and user interfaces of mixed reality (MR) and augmented reality (AR) for construction equipment. Bernold (2007) constructed a tele-operated pipe manipulator and its control scheme for improving performance in laying pipes. Comparative field test results showed that the tele-operation method improved productivity and eliminated safety issues compared to traditional methods. In the future, an unmanned remote construction site can be possible with all human beings situated away from the construction site and construction tasks being completed by various construction avatars.

With the increase in research effort focused on tele-operation applications for improving construction operations, the interface design of construction equipment remains an important topic for further study. Due to variation in operation functions and automation assistance with different construction equipment, the interface design can directly influence the efficiency and effectiveness with which operators can finish their tasks. Yokokohji et al. (2009) surveyed state-of-art robots for rescue missions and proposed design guidelines for the tele-operation interface, saying that the global view which covers the remote machine itself should always be included in the user interface for operators to monitor the overall situation while robots are working in challenging environments. This has also motivated further examination of the relationship between humans and tele-operated user interfaces.

In this research, we focus on the design of a user interface of a tele-operated crane. The purpose of this interface is to remove operators from the field, while continuing to provide them sufficient information for efficient and safe crane operation. The field perception abilities of crane operators need to be retained when they manipulate cranes remotely, therefore the interface utilizes augmented reality (AR) technology to guide operation and provide relevant warnings to prevent any unsafe operation. The viewing limitations of remote control are overcome by integrating the multiple views setting. Two evaluation studies has been built to validate these technologies through usability tests; their results are considered when adding more features and for further improvement. With the assistance of these technologies, the required information can be provided to the operators at the right time and place. This design procedure thus provides an ideal solution for ensuring the safety, quality, and efficiency of rigging tasks.

2. Evaluation Procedure

For designing a tele-operation crane interface, we built an evaluation procedure to evaluate the technologies we used and to improve the usability of the interface iteratively. This procedure is outlined in Fig. 1. The procedure is divided into two steps: the first step is technology validation; this validates candidate technologies to support the tele-operation crane interface. We have made two studies. In the first study, a prototype was built and the 1st interface with AR-enhanced erection path guidance and multiple views setting was designed. After the 1st usability test, we considered whether AR and the multiple views setting could potentially benefit crane tele-operation. The results obtained are used in the second step. By adding more features derived from conventional information available to operators, the 2nd interface was designed with consideration for human attention span and the 2nd usability test was conducted in the second study. The participants' feedback was collected for the next design cycle in the future.

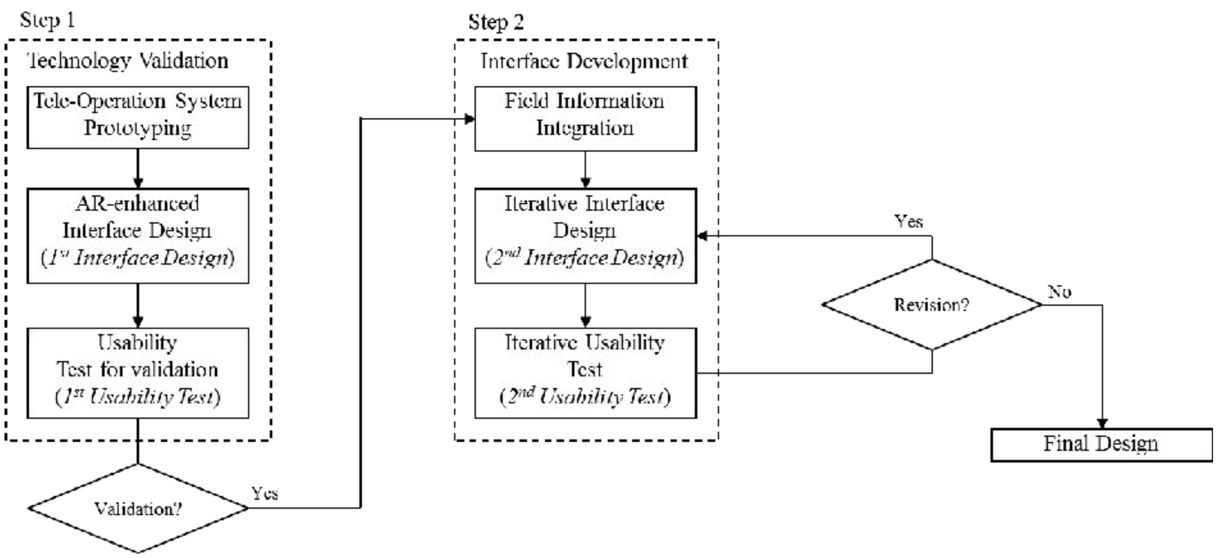


Fig. 1: The evaluation procedure for the tele-operated crane interface.

3. Interface Design

In the first step of interface design, we made a four-views interface with an AR virtual erection path on it. The detailed design proposal for this interface is presented in the following paragraphs:

***Multiple Views*:** In modern crane operation, the operator's work is often hampered by the operation location. The operator is therefore often compelled to conduct blind lifts while facing significant viewing difficulties (Shapira and Lyachin, 2009). To overcome these viewing problems, operators frequently rely on their skill and experience and also receive assistance from site workers. In a tele-operation scenario, these immersive field perception capabilities may be limited significantly due to gaps between the field and the interface, making crane operations even harder. Multiple capture devices that provide images covering different viewing angles of rigging objects in real-time can be useful for avoiding a blind lift situation and, at the same time, provide a global view captured from surrounding building for the operator to understand the general configuration of the crane in the construction site environment. As shown in Fig. 2a, the image capture devices can be mounted onto the crane body or at some distance from the construction site for monitoring purposes. The interface consists of four monitoring views from four sources: the top, right-side, and left-side views, and a global view of the crane. Thus, rigging objects and processes can be monitored from at least two views during rigging activities, and operators can carry out these tasks remotely using these views.

***AR display*:** The sense of movement and the site geometry information which is available to on site operators or provided by site workers are necessary for tele-operation. We integrated Augmented Reality (AR) technology to provide this information and serve as an extended eye of the operator, in order to control the crane remotely. AR is a technology that enhances human visual senses by placing virtual information, mainly in the form of computer-generated graphics, into real-life scenes. Unlike virtual reality, which builds a total virtual environment on computers, AR utilizes elements from the real world, such as images, captured videos and even vision from human eyes, and then projects virtual objects onto them. Using pose estimation (Kato and Billinghurst, 1999), AR makes it possible to add virtual information such as construction direction to real scenes so that the visual information available to the operator can be "augmented" with extra information. When combined with multiple views as shown in Fig. 2b, the operator can monitor the virtual erection paths during the operation and at the same time be aware of the elevation information of surrounding construction facilities.

An overview of the 1st interface can be seen in Fig. 3. It is designed for validating AR and multiple view technologies. We compared it to the conventional interface used in current crane construction.

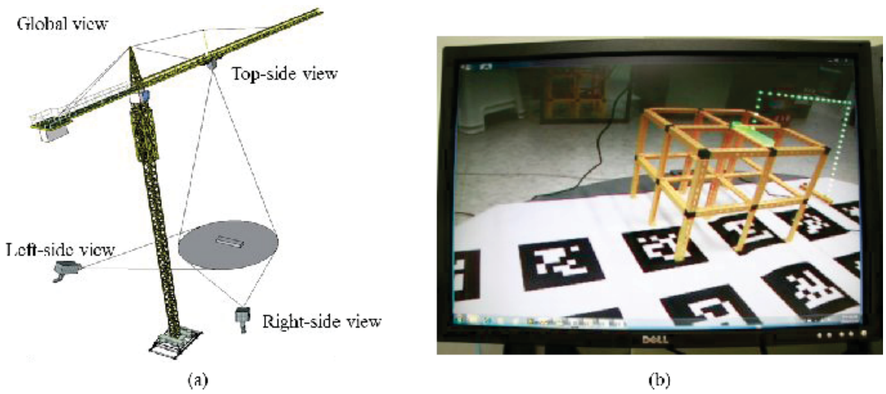


Fig. 2: The 1st interface design ideas: (a) multiple views setting, (b) AR virtual erection path.

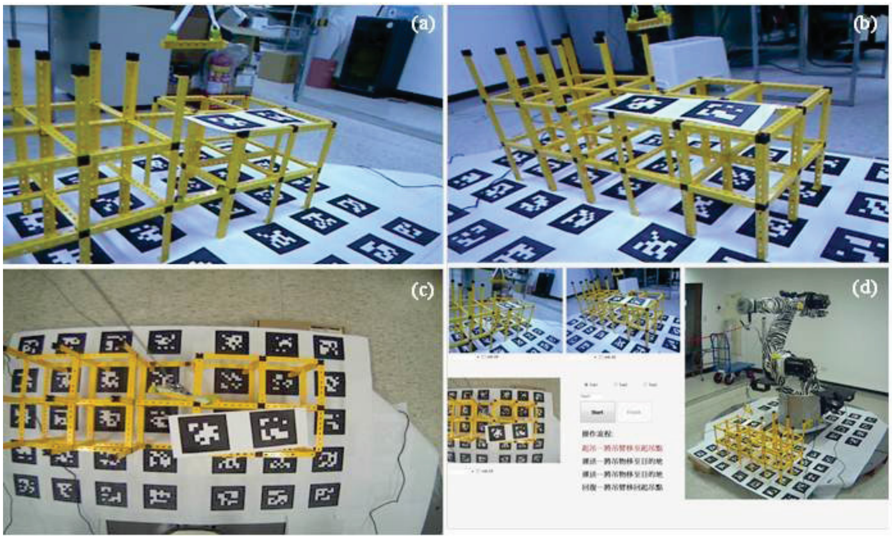


Fig. 3: The 1st interface: (a) left-side, (b) right-side, (c) top and (d) global/information view.

As the second step of evaluation procedure, the 2nd interface was designed. It was designed to integrate information needed in a common erection task and provide operable guidance. Taking into consideration the information flow and the limitations of human perception, we classify the erection information and display it using different methods, as described in the following paragraphs:

***Path Planning Guidance*:** For the purpose of interface design, we propose an approach for generating rigging paths to guide tele-operated cranes. This approach was developed to meet the requirements of operational safety, efficiency, and most importantly, operational feasibility for operators. We utilized a probabilistic roadmap (PRM) (Kavraki et al., 1996) as the path planning method to provide the operator with a collision-free path and instructions.

The basic idea behind PRM is to sample random nodes in space and connect nodes by checking that there are no obstacles in between them in order to create a feasible motion path from the starting point to the end point. Each sampled node can be linked using weighted edges according to distance and potential collisions between them. A graph structure is then generated. Along with potential collision issues, operational feasibility based on movement capabilities of the crane is also considered. Due to the nature of crane motion, the rigging trajectories tend to be composed of nearly horizontal and vertical lines. An algorithm for generating possible rigging paths, *pathSuggestor*, has been developed and the pseudo code is given in TABLE 1.

In the *pathSuggestor* function, we first generate a list of nodes, *n*, by randomly sampling in space. Then the cost matrix *M* is determined where its elements represent the cost between every combination of node pairs. We use an examination function, *operableCheck*, to evaluate whether a node pair satisfies the requirements of being collision-free and nearly horizontal or vertical. As can be seen in TABLE 2, if the slope of node pair P_iP_j is in the range $\pm\theta$ or $\pm\psi$, and there is no possible collision on P_iP_j, then the cost of P_iP_j can be assigned to be the distance P_iP_j. Otherwise, we treat P_iP_j as an unavailable path segment and set its cost to be infinite. The angle θ and ψ denote slope values which are close to horizontal and vertical. By building the cost matrix, *M*, through the function, *operableCheck*, we can use the *shortestPath* function to find an efficient solution for rigging guidance. The *shortestPath* function implements Dijkstra's algorithm (Dijkstra, 1959), used widely for finding the shortest path in a graph. This part can also be found using other famous algorithms for searching paths. All possible paths from the nodes list are checked, and the path with the shortest length then obtained is an efficient rigging path.

TABLE 1: The pathSuggestor algorithm

Algorithm *pathSuggestor*(P_{init}, P_{end}): finds collision-free, shortest, and operation feasible path for rigging guidance.
P_{init}, P_{end}: The starting point and destination of rigging objects.
P: The suggested path.
M: The cost matrix of every node pair in the space.
n: The list of sampled nodes.
n ← Randomly sample a group of nodes in the space
M ←*operableCheck*(n)
P ←*shortestPath*(P_{init}, P_{end}, M)
RETURN P

TABLE 2: The operableCheck algorithm

Algorithm *operableCheck*(M): finds horizontal and vertical movement segments for an operable path.
n: The list of sampled nodes.
M: The cost matrix of every node pair in the space.
P_iP_j: node pair (path segment).
FOREACH P_iP_j in n
IF $i \neq j$
IF (*Slope*(P_iP_j) ∈ [θ, -θ] **OR** *Slope*(P_iP_j) ∈ [ψ, -ψ]) **AND** *Collision*(P_iP_j) = false
$M[P_i, P_j]$ = Distance(P_iP_j)
ELSE
$M[P_i, P_j]$ = ½
ELSE
$M[P_i, P_j]$ = 0
RETURN M

***Attention-Based Information Classification*:** In this research, we have focused on how to display the information so that the operator can perceive the information effectively. We divided the information required by the operator into two categories, where each information category belongs to different views in the system interface. Also, depending on the priority, the information would be presented in different ways.

As shown in TABLE 3 the two information categories are erection progress and limitations. The information in the first category can help operators in completing the erection tasks. It includes lifting information, path, crane attitudes and the site scene. However, information in the second category would limit or interrupt erection tasks. This kind of information is concerned more with safety issues. It includes the working range of the crane, weight of the object, collision, human, and weather. This limitation information may affect the occurrence of accidents or injuries.

TABLE 3: The categories, priority, and display methods for the rigging information.

Category	Information	Description	View	Priority
Erection Progress	Lifting information	Lifting information includes the objects' name, ID, size, shape, and so on.	Ambient	Low
	Path	The operator has to consider the trajectory to move the rigging object to the destination.	Focused	Normal
	Crane attitudes	The crane's attitudes are used to show the angle and direction, or the length of the jib, cable, and hook.	Ambient	Low
	Site scene	The scene of the construction site.	Focused	Normal
Limitation	Working range of the crane	The capacity of the crane when the objects are being lifted to a different position. The lifting moment can exceed the capacity and cause the crane to overturn.	Ambient/ Alerting	High to Highest
	Weight of the object	The weight of lifting objects must be confirmed to be within the loading capacity of the crane.	Ambient/ Alerting	High to Highest
	Collision (excluding humans)	The operator should notice possible obstacles on the lifting path and any potential collisions.	Ambient/ Alerting	High to Highest
	Human	If there are people in the crane's working area, the operator must pay special attention.	Ambient/ Alerting	High to Highest

TABLE 3 is designed accounting for human perception factors in equipment operation. It also organizes the information by views and shows the priority based on different human attention levels. As Fig. 4 shows, Matthews et al. (2003) summarized previous research and developed the curve of awareness and attention, which we have drawn on in our design.

In our interface, we separate views based on divided attention and focused attention. Focused attention refers to how we attend to, or concentrate only on one stimulus; divided attention refers to how we distribute our attention over several things. As Fig. 4 shows, the system interface has three view types. The first one is the focused view, in which the information is displayed continuously. The second view is the ambient view, whereby information can be retrieved by the operator when required. The third view is the alerting view. The alerting view displays crucial information related to safety. This view would provide signals to shift the operator's attention from the original task when there is a risk of an accident occurring. The alerting view has three signaling levels corresponding to the level of danger. The green signal shows up when conditions are in the safe range; the yellow signal shows up to remind the operator to manipulate the crane with caution. A red signal warns of imminent danger and also provides information overlaid on the original screen, telling the operator to immediately resolve the dangerous situation.

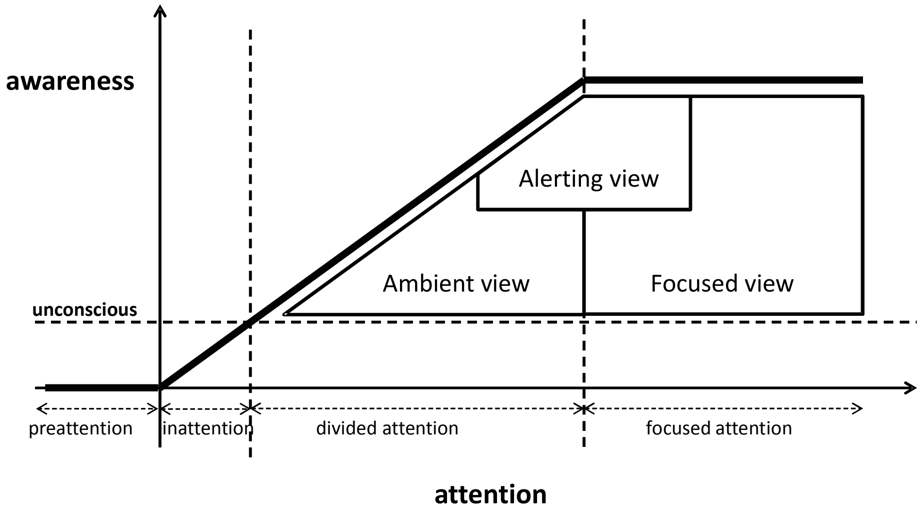


Fig. 4: Graph of human awareness vs. attention. (Modified by Matthews et al., 2003)

An overview of the 2nd interface can be seen in Fig. 5. The focused view includes the lifting path and site images, and is shown on the bottom two monitors. The ambient view, including the lifting conditions and crane attitudes, is shown on the top two monitors. The alerting view is different from the ambient and focused views. It is shown as the ambient view in normal time and will change its display state to attract operators' attention when dangerous situations arise. This form of information processing is crucial for detecting dangers and displaying necessary alert signals. For example, when the lifting object is close to the surrounding structure, the background color of the collision information will change to yellow. If the object moves even closer, the display color will change to red and a warning signal will also be displayed in the focused view.

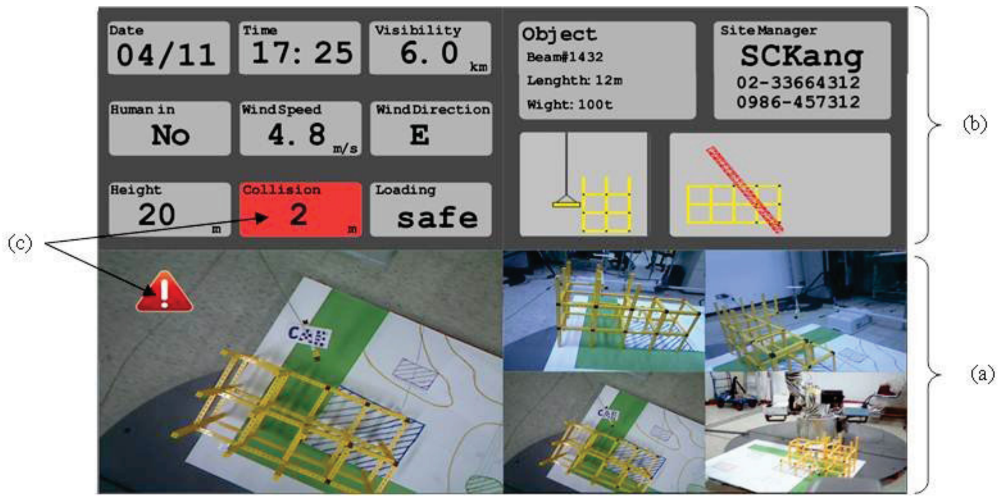


Fig. 5: The 2nd interface design: (a) focused view, (b) ambient view and (c) alerting view.

4. Prototype Implementation

For user interface evaluation, we used an industrial robot arm, KUKA KR 16 CR, with rigid body components and an end-effector to simulate cranes. An arm-like crane was developed by adding a cable with a hook to the end of the robot arm (Fig. 6a). The work area that the robot arm can reach is the simulated construction site. Operators operate the arm-like crane from outside this area using a control panel (Fig.

6b). Four webcams were positioned as follows: at the top of the crane's cable, on the right and left side of the crane, and the fourth at a distance from the site to provide a global view. Plastic components were used to simulate steel structures (Fig. 6c).

In the remote control cabin (Fig. 6b), a PC running Windows 7 (3.2 GHz 8-Core Intel Xeon with two nVIDIA GeForce 8800GT graphics cards and 2GB RAM) was set up to receive data and run the system. The computer was equipped with four 24" LCD monitors, each running at a resolution of 1920×1200 pixels to display the images and information from the cameras.

Fig. 6: Tele-operated crane prototype: (a) an overview, (b) remote cabin, and (c) simulated steel structures.

5. Usability Test

To evaluate the feasibility of the technologies being used, we conducted the 1st usability test for the 1st interface design. There were 30 participants in this usability test. The participants, chosen for their understanding of visualization technologies and the ease of familiarizing them with the developed system, were undergraduate and graduate students from a civil engineering background and most had taken related graphics or visualization courses. In the test, the participants were asked to complete erection tasks in order to evaluate the usability of the interface. Each participant needed to perform three tasks with three different interface settings: (1) only top view with oral guidance (Conventional Interface), (2) multiple views, and (3) multiple views with AR virtual path guidance. On completion of the usability test, the following details were recorded: time spent on tasks, task loading score for participants.

***Time spent on tasks*:** We recorded the time that participants took to complete the tasks. This could then be used to compare the efficiency of the erection activities using a conventional interface, multiple views and multiple views with AR guidance.

***Task loading score for participants*:** To evaluate loading of the participants when using the interface, we used NASA Task Load indeX (NASA-TLX) questionnaires, providing us self-evaluation results from the participants.. NASA-TLX is a standard questionnaire developed by NASA Ames Research (Biferno, 1985). It is a self-rating procedure for participants, which provides an overall workload score based on six weighted factors: Mental Demands (MD), Physical Demands (PD), Temporal Demands (TD), Effort (E), Performance (P), and Frustration (F). Before starting the tasks, participants need to assign a weight to each factor. After finishing each task, they rate the six factors. The task loading score, which represents the rating given to the interface by participants, is the weighted mean of the six factors.

For the 2nd usability test, the participants involved were again 30 undergraduate and graduate students. The comparison was between multiple views and attention-based interface. The simulated erection tasks that we asked the participants to perform were similar to the 1st usability test. Along with the test items recorded in the 1st test, we also recorded the occurrence of collisions in tasks and the utilization rates of views.

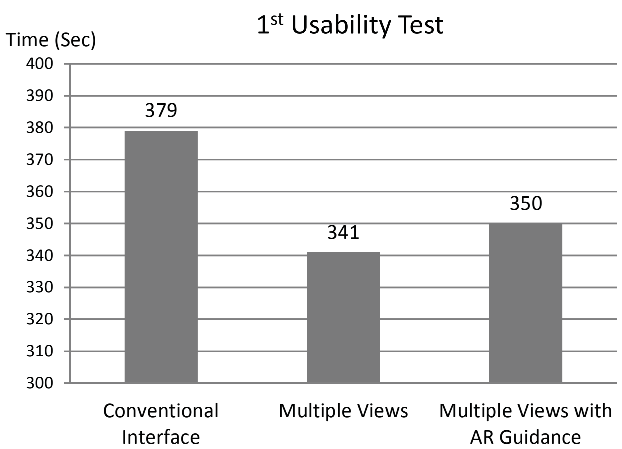
***Collision occurring in tasks*:** Along with the efficiency of performing tasks, safe operation is also an important issue. Therefore, any collision during erection activities, which include securing the rigging objects, moving the objects to the destination, releasing the objects and returning to the original position, are recorded.

***Utilization rate of views*:** We try to record the utilization rate of different views. This helps in identifying participants' perception patterns and we can verify whether the utilization rate is as we expected. Therefore, while the participants perform erection activities using the attention-based interface, we track which view the participants' eyes are looking at each second, and therefore calculate the utilization distribution for each view during the test.

6. Result

During the usability test, we record the test items described in the previous section. An α level of 0.05 was used for all statistical tests and analyses. This section summarizes the test analyses and results.

***Time spent on tasks*:** Fig. 7a shows the time the 30 participants took for completing each of the three simulated erection tasks in the 1st usability test. The average time taken by participants using the conventional interface was 376 seconds while participants using the other two interfaces took 341 and 350 seconds, respectively. For the 2nd usability test, the participants used only multiple views and the attention-based interface to perform the erection activities. The results are shown in Fig. 7b. The average time taken using only camera views was 276 seconds (SD 65.5), and the average time using the attention-based interface was 298 seconds (SD 63.9). This means that participants using only camera views take less time to finish the task, this was also the case in the 1st test; however, there is no significant difference in the t test (t=-2.03, p=0.52).



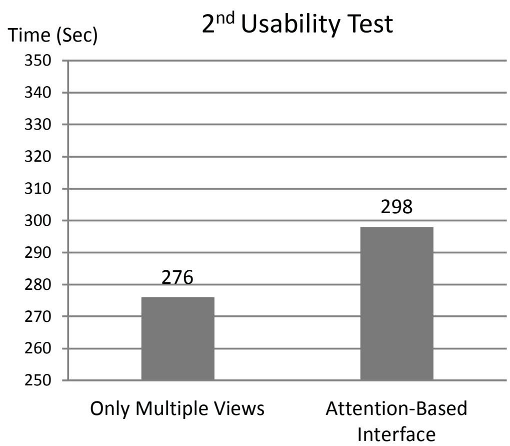


Fig. 7: The average time taken to finish tasks: (a) 1st usability test and (b) 2nd usability test.

***Task loading score for participants*:** Fig. 8a provides the average system scores given by participants to each operation interface. The scores given by each participant were the weighted means of the six factors.

From the figure, the scores for multiple views and multiple views with AR guidance interfaces are both better than the scores for the conventional interface. From Fig. 8b, the scores with the attention-based interface are higher than those using only multiple views in the 2nd usability test.

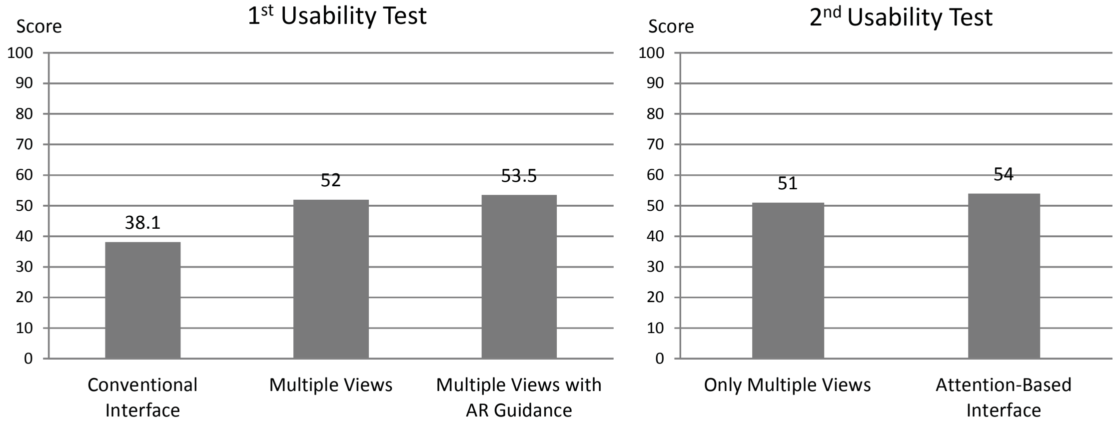


Fig. 8: The average system scores evaluated by participants: (a) 1st usability test and (b) 2nd usability test.

***Collision occurring in tasks*:** In the 2nd usability test, we also recorded the unsafe situation that occurred during erection activities performed using only multiple camera views and the attention-based interface. The unsafe situations represent that participant's manipulations which let rigging objects very close to surrounding obstacles. Most participants had zero or one unsafe situation during an erection activity. Among the 30 participants, as shown in Fig. 9, 14 people had unsafe situation using only multiple views, and 6 people had unsafe situation using the attention-based interface. Analysis using Chi-square test shows that the Pearson Chi-square is 4.8 and p is less than 0.05, which means there is a significant difference between these two interfaces.

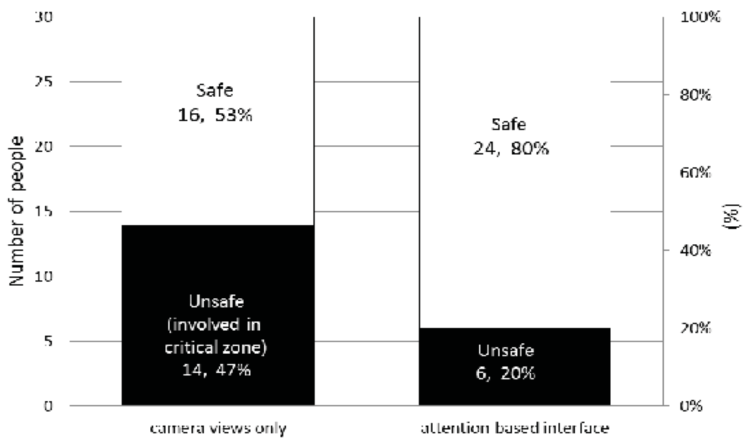


Fig. 9: Collision occurring in the erection activities.

***Utilization rate of views*:** The results are shown in Fig. 10. The participants spent about 92% of the time on focused views and about 8% on ambient views. The alerting views change the background color of the ambient views and superpose the attention signal on the focused views, which is used to get the participant's attention. Therefore, the utilization rate is not considered in this case.

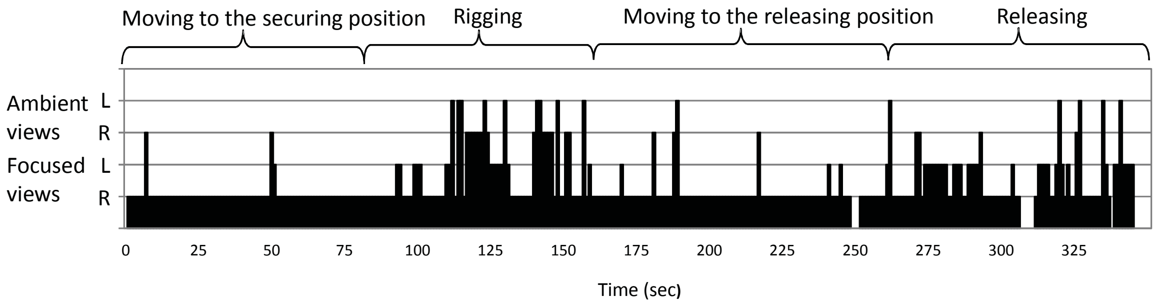


Fig. 10: Graphic of eye positions.

7. Discussion

From the results of 1st usability test, we can say that the multiple views and augmented reality technologies have been validated to be effectively integrated in the design of the tele-operated crane interface. These two interfaces on average reduce the time taken to complete tasks by 10% compared to the conventional interface (Fig. 7a). The loading of the participants was also 15% less, this can be seen from the 15% higher system score recorded using these two interfaces compared to the conventional interface (Fig. 8a). However, there is no significant different in completion time and system score between multiple views and multiple views with AR guidance. This implies that the potential benefit of AR technology used in the design of the 1st interface was not realized.

To increase efficiency, we tried to improve the interface by accounting for human attention span and to get more benefit from AR. According to the results of 2nd usability test, the participants spent less time on the tasks when using multiple views than they did when using the attention-based interface. This may be because the participants are being provided less information when using multiple views and also do not need deal with alert warnings. Therefore multiple views seem more efficient since using the attention-based interface involves taking time to react to the alerting view and preventing a collision. However, insignificant difference means that when the task is more complex, the attention-based interface will have an advantage in completion time.

Although using the attention-based interface is no more efficient than only using multiple views, it is safer. The results in Fig. 9 show that the use of the attention-based interface prevents over 57% of the collisions comparing to the use of only multiple views. The information available in the ambient view and focus view lets the participants understand the overall situation and perform the erection activities. Also, the warnings of the alerting view will alert the operators if they fail to notice a dangerous situation. This shows that an interface with AR assistance and an attention-based information layout does improve the safety of operation without significantly reducing efficiency.

The results in Fig. 10 show that generally, participants can complete most of movement of erection using focused views from cameras capturing images at different angles. They can use the information in ambient views when needed. This is consistent with our expectation. The frequency of viewing the ambient views can be related to the movements of the erection activities. We can see that when the crane is moving, participants spend less time looking at the ambient views. On the other hand, the utilization rate of ambient views increases when the crane is approaching its securing position or releasing position.

8. Summary and Conclusion

In this research, we designed user interfaces for tele-operated cranes to increase the efficiency and safety in construction. Following an evaluation procedure, we have conducted two studies. We utilized augmented reality to combine real images and virtual models, and provide path guidance in the interface. We also divided the different information into three views based on existing knowledge about the human attention zone. By going through two studies of evaluation, we improved the designed interface, taking into consideration how the operator would be able to receive the required information more effectively. From the two usability tests performed, we found that integrating multiple views and augmented reality technologies is effective in improving the design of a tele-operated crane interface. It is on average 10% faster in completing tasks and the loading of the operator is reduced by 15% on average compared to a conventional interface. The use of an interface with AR assistance with an attention-based information layout will improves safety of operation without significantly reducing efficiency. The number of collisions recorded was 57% less with the AR interface with attention-based information compared to the multiple views interface.

9. Acknowledgement

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DEVELOPMENT OF A ROAD TRAFFIC NOISE EVALUATION SYSTEM USING VIRTUAL REALITY TECHNOLOGY

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ABSTRACT: *This paper presents an advanced road traffic noise evaluation system using virtual reality technology based on the immersive projection technology. The key feature of the system is that the road traffic noise is provided for users by both auditory and visual information under various road and vehicle conditions. The geometric acoustic theory is employed for the simulation of traffic noise to realize the real-time simulation. The visual information of road traffic noise is created by the visualization system based on the Open-GL and CAVE library and the auditory information is created by the Max/msp. The present system is shown to be a useful tool to evaluate the road traffic noise in planning and designing road environment.*

KEYWORDS: *road traffic noise, auditory and visual information, geometric acoustic theory, immersive projection technology*

1. Introduction

The evaluation of road traffic noise is very important for planning and designing of road environment. There have been presented a number of numerical simulation methods in accordance with the development of computer. The theory for numerical simulation can be classified into two approaches; wave acoustic theory (Schenck, 1968; Nomura, 2008) and geometric acoustic theory (Yamamoto, 2010). The geometric acoustic theory is very useful for the development of the real time simulation system because the computational time is much shorter than the wave acoustic theory.

Generally, the numerical results are visualized using computer graphics (CG). However it is difficult to understand the noise level intuitively with CG, because the visualization is not auditory information. In order to overcome the problem, several systems that expose road traffic noise as the auditory information have been presented in the past studies (Nagano et al.1999, Mourant et al., 2003, Makanae et al.,2004). However, there have not been presented a system that presents auditory and visual information simultaneously under the various road environments. The present author developed a system (Tajika et al., 2009, Shibata et al., 2010) to expose the numerical results both with auditory and visual information using virtual reality (VR) technology. The ASJ-RTN Model 2008, which is the Japanese standard model for road traffic noise, was employed for the model based on the geometric acoustic theory. The system was designed as an interactive system which realizes the real time simulation. However the following problems are pointed out from the point of view of applicability; 1) The types of car are only available for standard cars and bikes, therefore the applicability of the system was limited in practical use. 2) The road environments in space and time are limited, for example, the plane road is only available and the CG scene is only available for day-time scene, and so on.

This paper presents an interactive road traffic noise evaluation system using virtual reality technology which can overcome above mentioned problems of our conventional system. In order to overcome the first problem, we add the other types of vehicle such as subcompact car, middle car and large car in addition with standard car and bike. Also, we add the new structures such as cut and bank for the road environments in space and prepare the night-time CG scene for the road environments in time to overcome the second problem.

The present system is shown to be a useful tool to evaluate the road traffic noise in planning and designing road environment.

2. A Road Traffic Noise Evaluation System Using VR Technology

The interactive traffic noise evaluation method is designed for the use of CAVE environments based on the immersive projection technology (IPT) (Wegman, 2002). FIG. 1 shows the concept of the system. This system provides two presentation methods for computed road traffic noise level, a) auralization function, which presents the auditory information of road traffic noise based on numerical result with the stereoscopic animation of vehicle run, and b) visualization function, which presents the stereoscopic iso-surface of the road traffic noise level by CG image with the road environment's CG. Using the auralization function, users can easily understand how big the simulation result's noise is, on the other hand, using the visualization function, users can easily understand the spatial distribution on the noise level.

The present system also provides following three characteristics. First, the observer can move to arbitrary position and can hear the road traffic noise that correspond with the position, since the road traffic noise level is computed in real-time using the position of observer (FIG. 2 (1)). Second, the observer can change the road environment; height of sound barrier, pavement type and passage years after pavement (Fig. 2 (2)). Third, the observer can change the vehicle conditions; vehicle type, vehicle speed and running distance of vehicle (FIG. 2(3)). Furthermore, the display function of the interface is developed in order to realize the second and third characteristics.

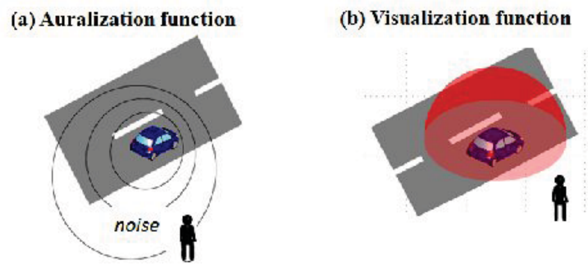


Fig. 1: Concept of the system (Shibata et al, 2010)

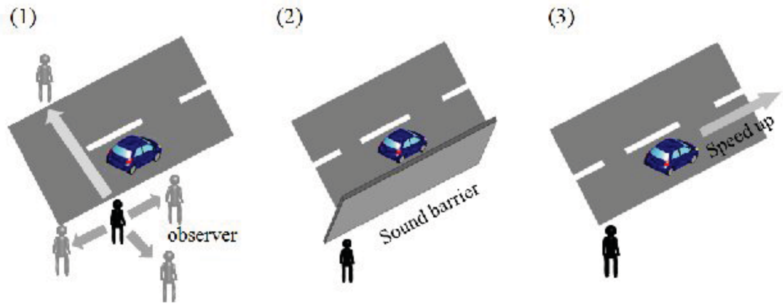


Fig. 2: Characteristics of the system (Shibata et al, 2010)

FIG. 3 shows the available road environments for the simulation in this system. The sound barriers, the elevated bridge and the building are already available in the conventional system. The cut and the bank are added to improve the applicability of the system. Moreover, as the vehicle is only able to run under the elevated bridge in the conventional system, the vehicle can run on the elevated bridge in the present system.

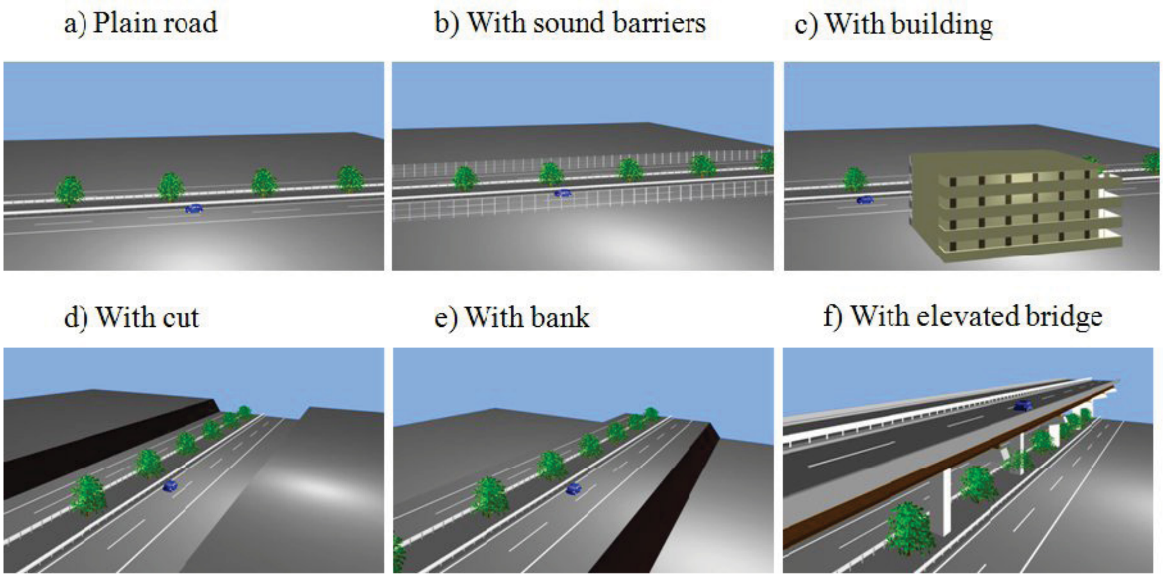


Fig. 3: The available road environment in the system

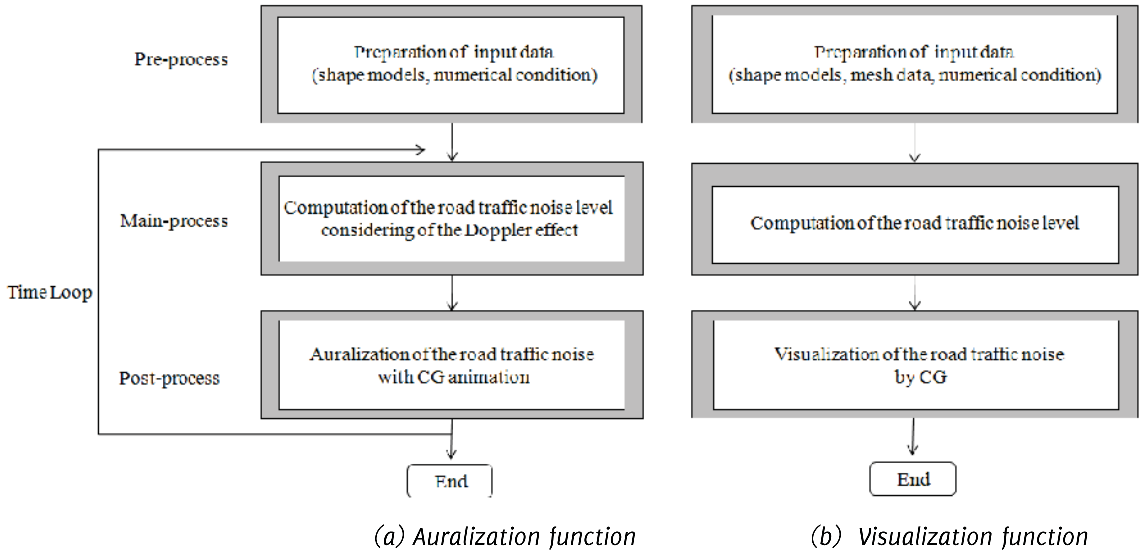


Fig. 4: Flow chart of the system (Shibata et al, 2010)

The procedure of this system is shown in the FIG. 4. The details of each process are explained as the following text.

2.1 Pre-process

2.1.1 Input data for auralization function

The shape models of the vehicle and surrounding environment of the roads (such as subcompact car, middle car, large car, cut, bank ,and elevated bridge etc, see in the FIG. 5) are created by the 3D CG and CAD software (3dsMax and AutoCAD: Autodesk). The polygons of shape models are reduced in order to speed up the rendering time. The input data for computation of the road traffic noise level are as follows; the position information of the vehicle, driving condition, and surrounding environment (such as the height of bank and cut) of the road. The position of the reputation sound point is captured all the time by the motion tracking device in the VR space.

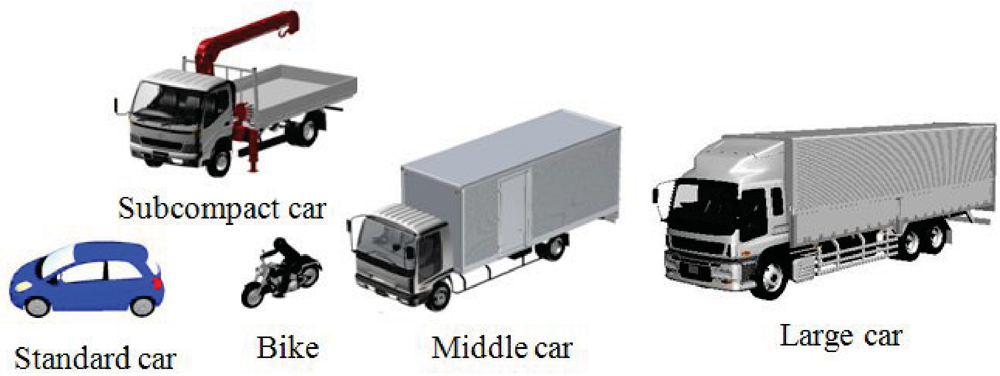


Fig. 5: The available vehicles in the system

2.1.2 Input data for visualization function

The mesh data is prepared in addition with the data for shape model and the data for computation of the road traffic noise. The mesh data is needed for the visualization of the iso-surface of the road traffic noise level by CG image. The mesh is based on tetrahedron element, the total number of nodes and elements are 67,626 and, 375,000 respectively (the mesh size to the horizontal direction of the road cross section, to the plumb direction and, to the depth direction, are assumed to be 2m, 1.2m, and 2m respectively). The value for iso-surface of sound pressure level to display is also specified for the input data for the visualization system.

2.2 Main-process

2.2.1 Computation of road traffic noise level

In this system, the road traffic noise level is computed by using the ASJ-RTN Model 2008 (Yamamoto, 2010) that is developed by the Acoustic Society of Japan. The sound pressure level is evaluated in real time by the model, since the model is based on the geometric acoustic theory.

The computation is performed using the position data of the vehicle, the observer, and the surrounding environment in real-time using a motion tracking system. The A-weighted sound power level of vehicle noise L_{WA} can be expressed as:

$$L_{WA} = a + b\log_{10} V + C \tag{1}$$

where a is the factor related to the types of vehicle (the values for standard car, bike, subcompact car, middle car and large car are assumed to be 46.7, 49.6, 47.6, 51.5, 54.4, respectively), b is the coefficient related to the vehicle speed, V is the vehicle speed, C is the correction term which is expressed as follows.

$$C = \Delta L_{surf} + \Delta L_{grad} + \Delta L_{dir} + \Delta L_{etc} \tag{2}$$

where ΔL_{surf}, ΔL_{grad}, ΔL_{dir}, and ΔL_{etc} are the corrections concerning with the noise reduction with drainage pavement etc, the change of road vehicle noise by the vertical slope, the directivity of vehicle noise and the rest factors, respectively.

The A-weighted sound pressure level L_A of direct sound which is propagated from vehicle is evaluated as:

$$L_A = L_{WA} - 8 - 20\log_{10} r + \Delta L_{cor} \tag{3}$$

Where r is the distance in a straight line between observer and vehicle, ΔL_{cor} is the correction concerning with attenuation factors that influences sound propagation, which is expressed as follows.

$$\Delta L_{cor} = \Delta L_{dif} + \Delta L_{grnd} + \Delta L_{air} \tag{4}$$

in which ΔL_{dif}, ΔL_{grnd} and ΔL_{air} are the corrections concerning with the attenuation caused by diffraction, the attenuation caused by grand effect, the attenuation caused by atmospheric absorption, respectively.

When it is necessary to consider about the plural propagations such as direct sound, reflection and diffraction sounds, the A-weighted sound pressure level is computed as;

$$L_A = 10\log\left(\sum_{i=0}^{i_{\max}} 10^{\frac{L_{A,i}}{10}}\right) \tag{5}$$

where $i_{\max}$ is the number of the sound propagations, $L_{A,i}$ is the sound pressure level corresponding the sound propagation. The Doppler effect is also considered in this system (Tajika et al., 2009, Shibata et al, 2010).

The computational method for new road environments, elevated bridge, cut and bank, are described in the followings.

1. The computational method considering an elevated bridge.

   FIG. 6 shows the computational method for the case with an elevated bridge when the car passes on it.

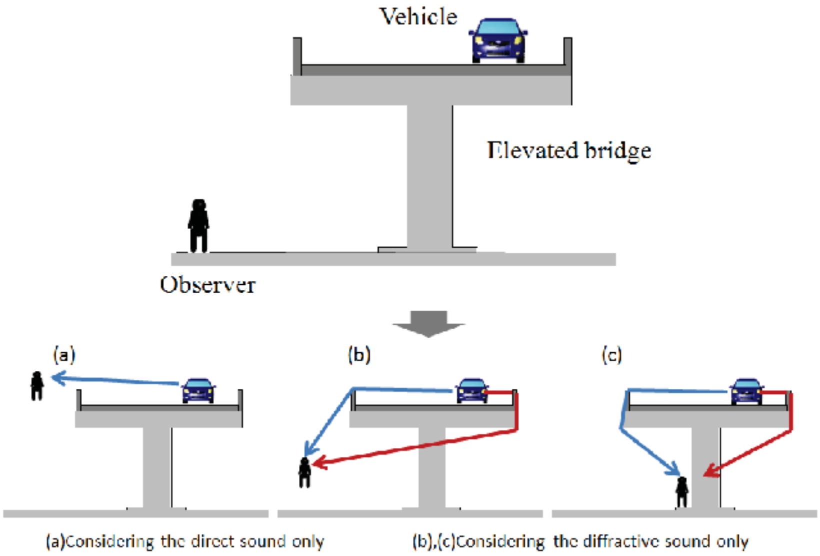


Fig. 6: Computational method with an elevated bridge

   When observer is located at the seeable area of the car, only the direct sound is considered as shown in FIG. 6. In case of FIG. 6 (b) and (c), the A-weighted sound pressure level L_A around the elevated bridge is computed by equation (5) using two diffraction sound propagations.

2. The computational method considering a bank.

   FIG. 7 shows the computational method for the case with a bank.

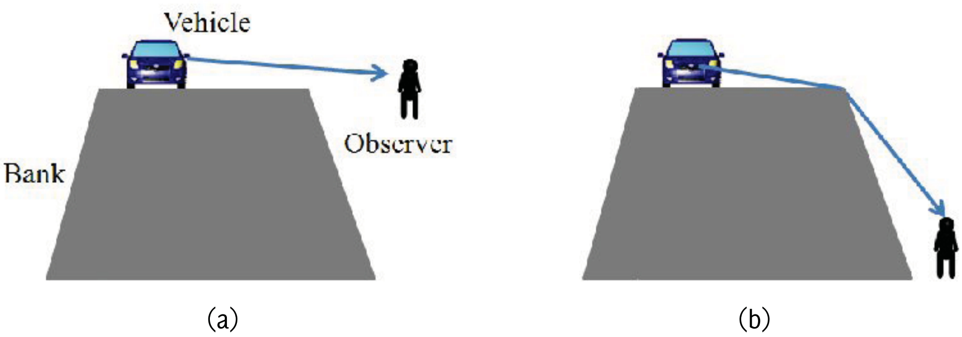


Fig. 7: Computational method with the bank

Under this situation also when observer is in the seeable area of the car, only the direct sound is considered as shown in FIG. 7 (a). On the other hand, only the diffractive sound is considered when observer is not located at the seeable area as shown in FIG. 7 (b).

3. The computational method considering a cut.

FIG. 8 shows the computational method for the case with a cut.

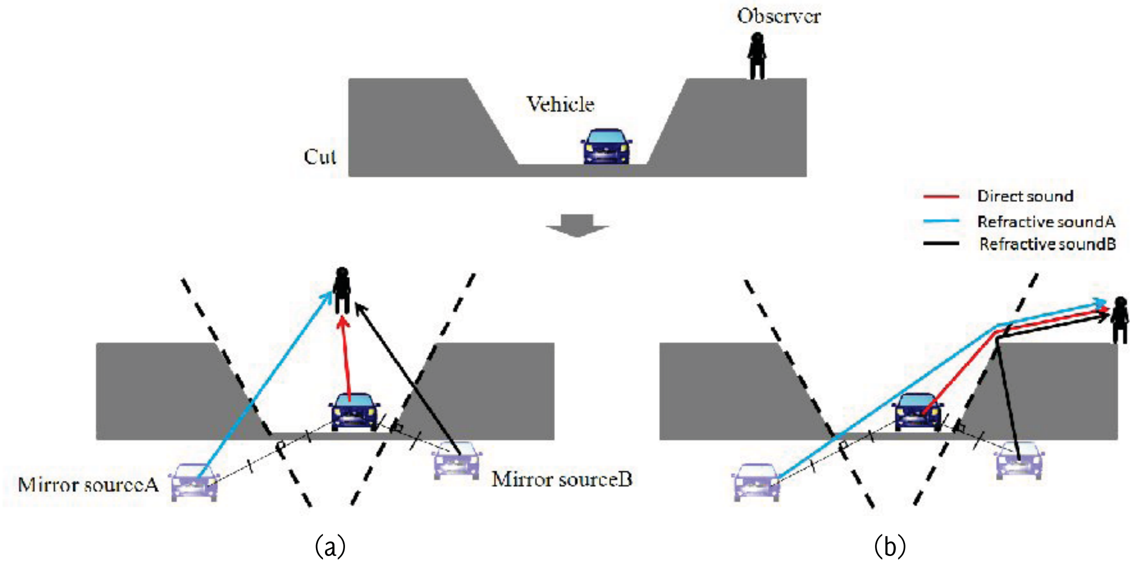


Fig. 8: Computational method with the cut

The top figure of FIG. 8 shows the situation for sound source and observer's point. Considering the effect of the cut, the mirror images of sound source are created for computing the reflective sound. The bottom two figures show the computational positions including the mirror source. When the sound sources are able to see from the position of the observer such as case (a), three numbers of the propagations are computed, not only direct sound from the sound source, but the reflective sound from the mirror source A and the reflective sound from the mirror source B. On the other hand, in the case when the sound sources are unable to see such as case (b), two different computational ways are employed for the computation of ΔL_{dif} in equation (4) as.

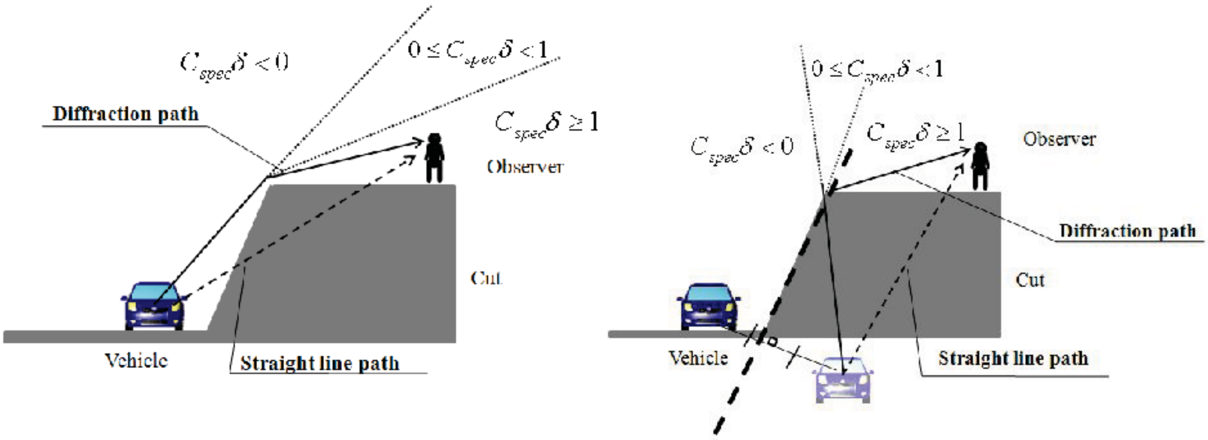
For the case for sound source (see FIG. 9 (a)):

$$\Delta L_{dif} = \begin{cases} -20-10\log_{10}(c_{spec}\delta) & c_{spec}\delta \geq 1 \\ -5-17.0\times\sinh^{-1}((c_{spec}\delta)^{0.414}) & 0 \leq c_{spec}\delta < 1 \\ \min\left[0,-5+17.0\sinh^{-1}(c_{spec}|\delta|)^{0.414}\right] & c_{spec}\delta < 0 \end{cases} \quad (6)$$

For the case for mirror sound source (see FIG.9 (b)):

$$\Delta L_{r} = \begin{cases} -20-10\log_{10}(c_{spec}\delta) & c_{spec}\delta \geq 1 \\ -3-19.3\times\sinh^{-1}((c_{spec}\delta)^{0.33}) & 0 \leq c_{spec}\delta < 1 \\ 0 & c_{spec}\delta < 0 \end{cases} \quad (7)$$

where c_{spec} is constant related to the pavement type, δ is a different length between a straight path and a diffraction path from the observer to the vehicle (see FIG. 9). In the equation (6), if the sound source can be seen from the observer directly, the sign of δ is to be a minus, and if a is larger than b, $\min[a,b]$ is to be a.



(a) From sound source (b)From mirror sound source

Fig. 9: the example of the diffraction of sound

2.3 Post-process

2.3.1 Auralization of the road traffic noise

The stereoscopic CG animation is presented with the auditory information at every time step. The CG image is created by the visualization system based on the Open-GL and CAVE library. The auditory information of road traffic noise is created using the Max/msp (Akamatsu and Sakonda, 2006). The road traffic noise level, the frequency and the wave file of vehicle noise are prepared for the input data for Max/msp. Those three data are prepared at every time step for creating the CG animation with the auditory information.

2.3.2 Visualization of the road traffic noise

The CG image of the iso-surface noise is created by the visualization software developed by Open GL and CAVE library. User can specify the sound pressure level by using the controller.

The sound pressure level is computed at every nodes of the mesh for visualization. The iso-surface of the sound pressure level is created at element-wise using the linear interpolation function. In order to improve the solidity, the rendering technique is employed for the visualization.

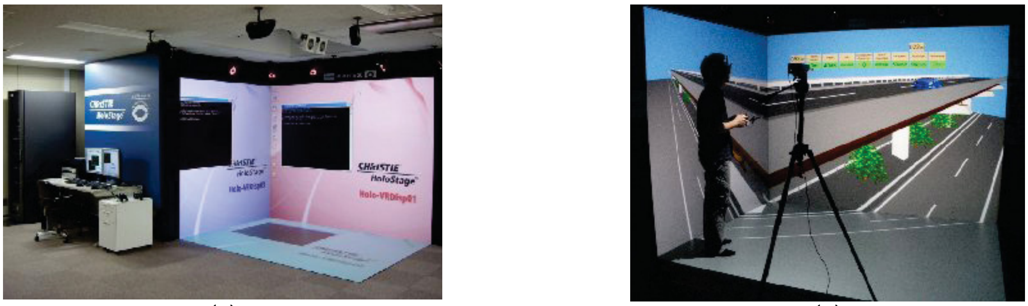
Above the both functions, the additional types of cars are available to choose for simulation. Moreover the scenes such as day time and night time are available to change by using controller as shown in FIG. 10. Measuring the brain waves is also done for the one of the other study to investigate the relation among the human stress, the road traffic noise and the time scene by using the present system.

Fig. 10: The scene of the day time (left) and night time (right)

3. Creation of the VR Space

3.1.1 VR system based on IPT

The IPT (Immersive Projection Technology) is employed for VR technology and the immersive display is employed for VR display. FIG. 11 (a) shows the VR system "HoloStage" of Chuo University. This system is composed of three large and flat screens and high-performance projectors corresponding to the screen. The front and side screens are transmissive ones and the bottom screen is reflective one. The VR space is created by projecting the image on the front and side screens, and the bottom screen. This system has 7.1ch sound speakers and the VR space is created by the auditory information and the visual information. FIG. 11 (b) shows the scene that the observer uses the auditory function of the system.



(a) (b)

Fig. 11: VR system

3.1.2 Application example

The present method is employed for the computation of sound pressure level using different vehicle type using the plain road environment as shown in FIG. 12. We compared the computed results with the measured results and we verified the good agreement each other. FIG 13 shows the unit pattern that is measured by the sound level meter. It can be seen that the different results are shown depending on the different types of vehicle. The verification of the result is left in the future work.

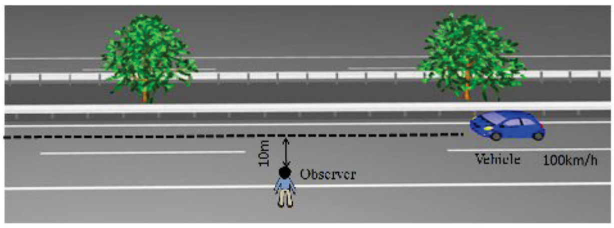


Fig. 12: Application condition with different car (Auralization function)

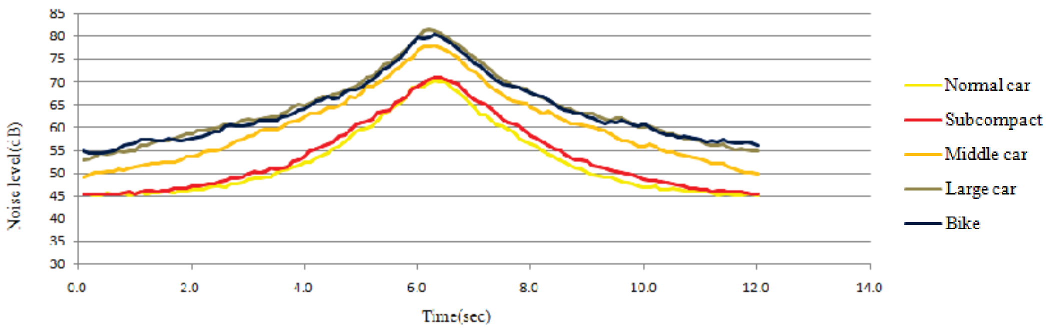


Fig. 13: Application example with different car (Auralization function)

Next, the present system is employed for the various road environments as shown in FIG. 14.The vertical position of the observer is shown in FIG. 14. FIG. 15 shows the unit pattern that is measured by the sound level meter.

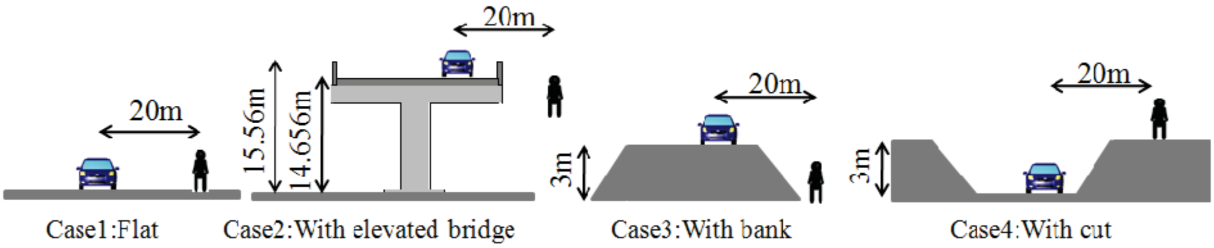


Fig. 14: Application conditions with different road environment

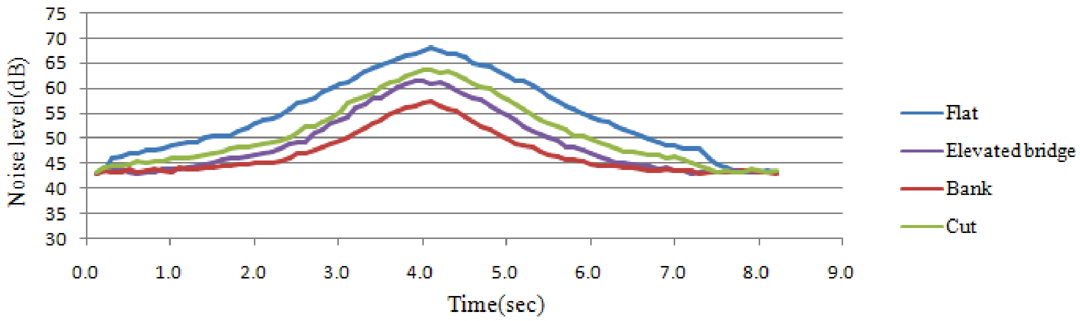


Fig. 15: Application example with different road environment (Auralization function)

In order to check the validity of the results, the visualization function is employed. FIG. 16 shows the distribution of iso-surface of sound pressure levels (50, 55 and 60dB). The condition is as same as shown in FIG. 14 except case 1 because there are no obstacles in the case 1. All of those are with new added structures in this paper. It can be seen that the noises are transmitted reasonably with reflection and diffraction, in accordance with the geographical conditions.

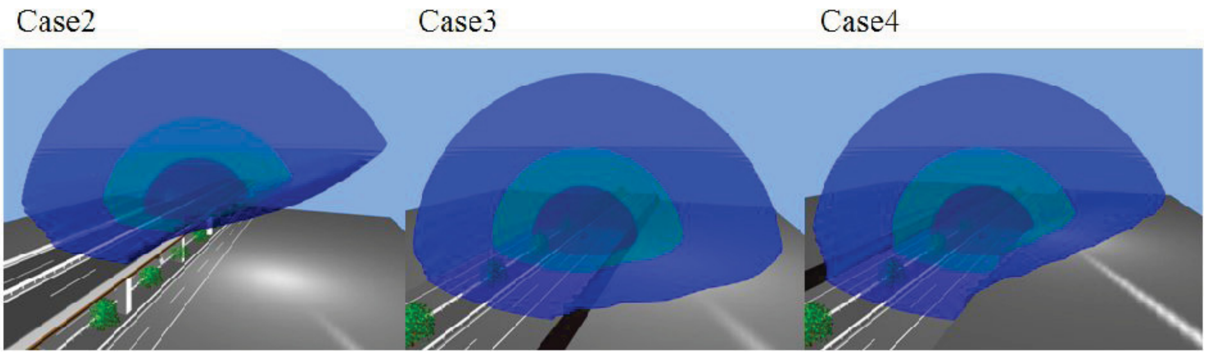


Fig. 16: Application example (Visualization function)

4. Conclusion

In this paper, the development of a road traffic noise evaluation system using virtual reality technology has been presented. In order to improve the applicability of the system, the new structures such as cut and bank for the road environments in space have been added and the night-time CG scene for the road environments in time have been prepared. Moreover, the several types of vehicles are added for expanding the available simulation.

From the results obtained in this paper, it can be concluded that the present system provides a useful tool to predict the road traffic noise in planning and designing stage of road. Moreover, the several types of vehicles have been considered to simulate the real traffic problems.

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OPERATIVE EXECUTION PLANNING CONCERNING WEATHER FORECAST DATA BASED ON CONSTRAINT-BASED SIMULATION

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ABSTRACT: *The execution process is known as complex process because of uncertainties and changes during the process. These changes affect the estimated construction time and cost. Many studies have been conducted to demonstrate that bad weather conditions clearly affect construction performance resulted in construction duration extension and cost overrun. Especially because of the complex variation of weather conditions, it is necessary to control the schedule during the execution process. To address this aim, this research provides a simulation model which supports managers in controlling operative schedule whenever bad weather events happen. Short term weather forecast is used as input data which guarantees the reliable and practicable results of the model. Weather impact is integrated into the construction process as constraints which are checked for the fulfillment during a period of the weather-considered execution schedule. Simulation model is getting more popular in solving problems of construction processes. In the simulation environment of Tecnomatix Plan Simulation program, interacting with other available components, a WEATHER component is developed to generate weather data and make the weather impact decisions. Managers often depend on their personal experience to account for the weather impact on schedule. Because of the variation in managers' experiences, the results can be widely different between managers. To support them in dealing with bad weather problems, this simulation model provides a flexible environment to experiment weather-related construction strategies aiming to reduce non-working time or unproductive working time on site.*

KEYWORDS: *Weather impact, constraint-based simulation, weather-related construction strategies*

1. Introduction

Everyday life on construction sites is commonly characterized by enormous pressure of construction time and cost. It is the fact that construction projects are subject to multiple constraints and changes due to various influences during execution (Bargstädt and Ailland 2008; Bargstädt and Ailland 2009; Mack and Wimmer 2011). In the planning stage, the estimation of construction time is a challenge because of a number of factors which should be considered in order to make the construction time more practicable and acceptable to each contracting parties. Even if the construction time can be established in exact terms, there are unforeseeable or unexpected factors which cause delays during executing process. One of the uncertainties, which clearly affect construction performance, is bad weather conditions. In the executing stage, the actual weather conditions are reasons of the time deviation from the formerly optimized plan. When exceptional adverse weather causes construction delays or cost overruns, contractors often submit claims which request extension to the project completion time (Moselhi and El-Rayes 2002). Investigating 24 projects in Western Canada, (Semple, Hartman and Jergeas 1994) concluded that weather was the second leading causes of delays, claims and cost overruns. Inclement weather was also suggested as the most frequent reason for delay claims in 67 surveyed projects in Hong Kong (Yogeswaran, Kumaraswamy and Miller 1998). A number of studies have been researched on the impact of weather on construction schedules. These researches have usually studied the influences of weather on the whole construction scheduling in planning stage based on historical weather data or typical weather patterns of local areas (Le and Bargstädt 2010). However, the variation of weather conditions is often complex and not always the same as how it used to be. Therefore the abilities to identify weather parameters and forecast their impact on construction activities are important for planners to make right decisions when encountering weather problem during executing stages. It is even more important that what managers should do to reduce the impact of weather on the construction performance.

Currently, simulation is getting more popular in supporting decision-making. Even if the results are not optimal, they provide appropriate solutions for complex problems (Bargstädt and Ailland 2009). This paper aims to describe a simulation model, which considers the impact of weather forecast data on the operative execution planning based on constraint-based approach. By using this model, the current state of construction process and the 5-day weather forecast data are defined as the input data and the output data is the appropriate weather-related schedules. Besides, the daily weather related construction strategies are discussed aiming to reduce unproductive working time on sites during bad weather conditions.

2. Analysis of Weather Impact on Construction Processes

Adverse weather conditions cause project delays, disruptions and the possibility to dispute between project parties. Adverse weather events such as hurricane and its aftermath not only cause project delays regionally but also nationally because of the shortage of construction materials, equipment (Nguyen et al. 2010). The impact of weather on the construction performance depends on various factors such as the type of construction activities and trades, the experience and weather-adaption of workers, the experience of construction mangers to deal with risks caused by inclement weather events. In the previous publications, the authors divided the impact of weather into three cases: (1) temporarily prevent workers from working, (2) affect the delivery of material by preventing crane from operating, (3) reduce labour productivity causing the extension of activities' construction duration (Le and Bargstädt 2010a; Le and Bargstädt 2010b). In what follows, this paper discusses more in detail about these three weather-impact situations and their impact factors.

Non-working time on site due to adverse weather conditions

In the first case, the definition of weather conditions which prevent workers from working depends on the definition of weather threshold values and the type of construction activities. Inclusion of weather thresholds is important to quantify the non - working duration. The weather events, which cause temporarily stop working, are usually related to heavy rain, snow, extremely strong wind and the adverse conditions of temperature and humidity (Le and Bargstädt 2010a). Therefore the thresholds of these weather events should be determined. Extremely hot weather can cause injuries, heat exhaustion and heat stroke; whereas working in extremely cold weather may lead to freezing. The threshold of wind velocity should be determined because strong wind condition may cause accident for workers working outside and at the high level, for example on the scaffolding. Heavy rainfall and snow are also reasons which interrupt the execution processes. It is obvious that how rainfall or snow affects the execution processes depends on the type of construction activities, the intensity of the weather event and the onsite drying conditions. Intensity of rainfall relates to the rainfall thresholds while the other two factors relate to the type of work and lingering days (Nguyen et al. 2010). The reason is the effect of weather on construction processes may not end when the rainfall event stops. Indeed it may extend beyond the rainfall duration due to site conditions, type of construction activities, drying time and accumulated water on site (Finke 1990; Nguyen et al. 2010). The extension time is called lingering day.

The definition of threshold values depends on some factors such as trades, natural and social factors (Nguyen et al. 2010). For example, The Tennessee Department of Finance and Administration (TennDFA 2007) established threshold values as 2.54 mm for precipitation (rain, snow, or ice), temperatures not above the value that is required for the work of the day and wind velocity not above about 11 m/s for its projects. Studies indicated that temperature above +43°C and below -23°C with humidity above 50% are intolerable, and workers should cease working (Koehn and Brown 1985). The National Aeronautics and Space Administration (NASA) BCA considered the severe weather as less than 0.254 mm of rainfall while the Armed Services BCA (ASBCA) in a case rejected this value and used a daily severity of 12.7 mm (Finke 1990; Nguyen et al. 2010).

The type of work is also an important factor which determines the impact of weather on working condition on site. Certain activities are sensitive to weather parameters while others may be not due to their characteristics. Those characteristics are e.g. duration, exposure, used material and used equipment. How a project is sensitive to weather also depends on its phase (Nguyen et al. 2010). (McDonald 2000) suggests that the initial site phase of a construction project is usually more sensitive to weather than the dried-in phase. Therefore the stress on the notice of weather conditions may be different during the execution process.

Non-working duration due to weather should be decided based on the consideration of all threshold values, type of affected construction activities (McDonald 2000). The comparison of threshold values and the actual weather data might be necessary if the construction parties dispute whether it is working or non-working time (Kenner et al. 1998).

Disable crane operation due to strong wind condition

This case happens when the wind velocity is beyond the maximal permissible value for the crane to be operated safely. The consequence is the interruption of the material delivery, which contributes to the schedule delay. If the crane cannot be operated, the light material can be hoisted to the low level by hand if there is no other available transport equipment. However it also reduces the productivity of the construction performance. In this case, the threshold value of wind velocity for crane operation is needed. This value is defined normally based on type of crane, operation condition and hoisted material. Following an instruction of crane operation, it is suggested that the maximal permissible wind velocity to operate a crane is about 13 m/s (Le and Bargstädt 2010a).

Lost labor productivity

Different from most other manufacturing industries, building construction is usually performed in outdoor environment, i.e. people have to experience hot or cold temperature, uncomfortable combination of temperature and high humidity, encounter days of raining or snowing, strong or even dangerous wind and storm. These adverse weather conditions can cause loss of labor performance efficiency. Temperature causes heat stress when people have to expose to high temperature in an extended period of time. The consequence is “the physiological effect of heat stress usually begins with a dulling of senses and a loss of coordination” (Adrian 1987). On the other hand, extremely cold weather causes freezing, which may lead to work accident. Humidity is an important factor which has varying effects, often detrimental, on worker’s health. It is proved that humidity level affects heart rate. Humidity levels above worker’s comfort range cause stress, especially in combination with temperature and/or wind conditions. It may be difficult to quantify the impact of humidity on workers, but it is little doubt that the impact is negative and not controllable (Adrian 1987). How significant wind condition affects construction productivity depends on the location of construction site. It is stronger effect when the construction site is located on a clear, few obstacles or buildings around area. A cold wind cools fingers and toes if they are exposed and makes hand and feet numb. This can obviously reduce efficiency, especially labor-depended construction activities. Furthermore high wind speed or gustiness may diminish control and steadiness in walking. It is the fact that the effect of weather parameters on labor performance is various from one to other location, also depends on workers' experience and their weather-adaption.

It is obvious that lost productivity due to adverse weather must be incorporated into the schedule. Therefore managers can accurately estimate construction time, cost as well as plan and control projects. It is important that managers can quantify the impact of weather parameters on labor productivity. This is usually achieved by assessing the impact on task duration. To do so the impact directly on task duration or on task productivity should be made. Some studies have been conducted to establish the relationship between labor productivity and weather parameters using regression analysis (Koehn and Brown 1985; Thomas and Yiakoumis 1987) or neural networks (Wales and AbouRizk 1996). Another alternative is to interpret experts' knowledge using fuzzy logic to identify the impact of weather parameters on sensitive activities (Shahin, AbouRizk and Mohamed 2010). In this research, the authors utilized the outcomes of the research conducted by Koehn and Brown (1985), which was mentioned in detail in previous publication (Le and Bargstädt 2010a). Thereby a table which represents function between productivity factor and effective temperature for general construction was established using regression analysis based on historical data. A total of 172 data points were investigated for general construction (Koehn and Brown 1985). A final result was achieved, which represents productivity as percentage of ideal productivity for a wide range of effective temperature and humidity. For more detail, please refer to our previous publication (Le and Bargstädt 2010a).

3. Description of Simulation Model

The proposed simulation model has been developed using constraint-based approach, which was developed within the cooperation "Simulation of Outfitting Processes in Shipbuilding and Civil Engineering" (SIMoFIT) performed by the Bauhaus-University Weimar and Flensburg shipyard company. Thereby construction process requirements e.g. technological dependencies, resource requirement etc. are described as constraints (Beißert, König and Bargstädt 2007). The idea is that work steps can only start when their certain constraints are fulfilled. This approach is implemented by extending the Simulation Toolkit Shipbuilding (STS) of the SimCoMar community (König, Beißert and Bargstädt 2007). The STS uses the discrete-event simulation program Plant Simulation provided by UGS Tecnomatix. This popular simulation environment enables modeling, simulating and visualizing of production systems and processes. A collection of STS components are available in program for users to simulate construction process e.g. resource administration, constraint manager, assembly control and so forth. Furthermore users can solve many construction problems by using this simulation program.

In this research, the authors have developed a simulation model to support managers in revising operative schedule during executing process when encountering bad weather problems. To address this aim, construction processes are simulated using available STS components and a WEATHER component has been developed to consider the weather impact. The 5-day weather forecast data and three cases of weather impact discussed in previous section are implemented in the model. In what follows, we discuss the input, output data of the model, and then the WEATHER component and the simulation concept are described.

3.1 Input and Output data

The first important step to build the model is collecting input data, which are the data of construction process, weather forecast data and data about the effect of weather on construction activities (Table 1). Input data which are used to simulate construction process are necessary for available STS components such as *Assembly Control, Resource Administration, Material Administration* and *Constraint Manager*. These data should be collected as accurate as possible on site. At this moment, the input data cannot be generated from CAD or Microsoft Project; indeed they need to be manually typed in tables. Depending on the occurrence time point of bad weather events and the controlling demand of managers, the start date of the operative construction process can be the start date of the project or the intermediate date of the execution process. Hence the other information of the construction process at every controlling time can be the whole schedule or only part of it.

Table 1: Input data

Type of input data	Examples
Time and date	Start construction time and date of construction assignments (building sections) and material delivery
Construction assignments	Assembly position, dimension and number of construction assignments
	Assembly position, dimension and number of elements
Construction tasks/ work steps	Name and execution duration of tasks/ work steps
Constraints	Execution sequences of construction assignments
	Execution sequences of work steps
	Technological dependencies of constructions assignments and work steps
	Other process constraints
Resource	Number and qualification of workers, equipment
	Working hours on site
Weather	Weather forecast data including date, time and value of weather parameters
	Weather threshold values
	Relationship between weather parameters and productivity

Weather forecast input data are input into WEATHER dialog box (Fig. 1). As can be seen from Fig. 1, time, date and some weather parameters are necessary for this simulation framework, which will be stored in a table inside the WEATHER component by pressing *Upload Data* button. Weather forecast data used in this simulation model is a 5-day forecast. Weather is known as the natural phenomenon which is difficult to forecast exactly and not always the same as the historical data. Therefore short term weather forecast is used in this model in an effort to provide managers a forecast weather-related schedule as practicable as possible. Weather forecast data can be achieved from public source or from the nearest weather station. In this research, main weather parameters are considered such as temperature, humidity, wind velocity

and precipitation. In order to collect data about the effect of weather parameters on construction activities, the necessary step is to go over the work breakdown structure of the construction process and investigate which work steps are sensitive to weather effects and which are not. Therefore the data collected for weather-sensitive work steps include influencing weather parameters, stopping conditions and relationship between influencing parameters and those work steps. For example, the labor-dependent work steps are effected by effective temperature and relative humidity (Koehn and Brown 1985) and also the intensity of precipitation and wind velocity.
The output data of the simulation model is the weather - considered schedule, which shows the delays due to bad weather conditions. Whenever bad weather events occur, managers may need to control the schedule regarding to these events. Considering the 5 - day weather forecast, the 5 - day weather-related schedule is analyzed. It is important to know how the delays of 5 - day weather - related schedule affect the remaining schedule. This information may help managers to forecast the effect of short term bad weather conditions on the whole schedule. Besides, the performance analysis of weather - considered schedule is also a result of this model. The analysis may include the productive working time on construction site, the number of delayed work steps and so forth.

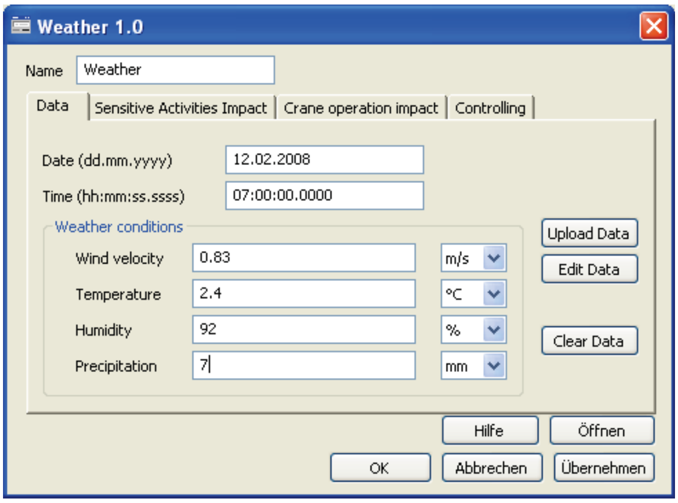

Fig. 1: Weather input data

3.2 WEATHER component

WEATHER component is a developed network which concerns the impact of weather on construction process. Its dialog box is shown in Fig. 2. *Sensitive Activities Impact* and *Crane operation impact* tabs of the dialog show cases of weather impact discussed in the previous section. For the impact of bad weather on weather sensitive work steps, the weather thresholds and function of weather parameters and labor productivity or duration are needed. Weather thresholds for each type of work steps are manually listed in a table which will be assigned to its respective field on the *Sensitive Activities Impact* tab. For example precipitation thresholds for all work steps of a façade construction which are performed outdoor can be 6mm which is understood as heavy rain. Two options for users to estimate the impact of weather parameters on labor productivity or task duration are available (Fig. 2). Since the function of productivity and weather parameters from research conducted by Koehn and Brown (1985) is utilized, the respective option is chosen. The *Crane operation impact* tab displays information about the impact of wind velocity on crane operation. The needed information is the type of transport equipment which can be crane or other equipment. Besides, transport by hand to a defined high level is also a possibility. If transport by crane is used then crane information and wind velocity threshold are needed.

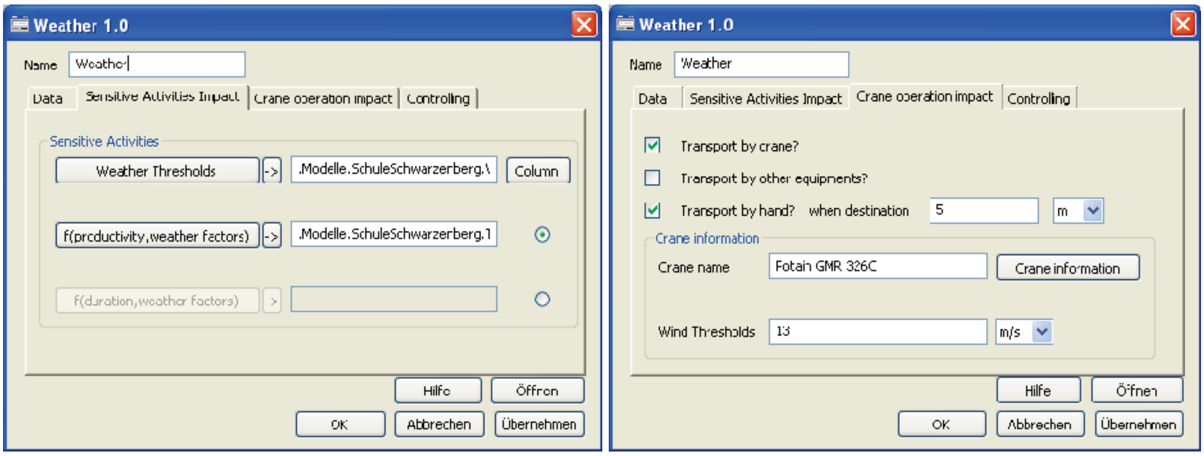

Fig. 2: Cases of weather impact are expressed in WEATHER dialog

WEATHER component is responsible for generating weather conditions for upcoming days and making weather - related decision based on the user's defined weather effect data. When a new work step starts, point of time is recorded by a simulation clock. Based on this information, WEATHER generates the weather data. In order for making decision, a list of next executable work steps is transferred from *Constraint Manager* component to WEATHER. Then weather - sensitive work steps and its weather effect are analyzed by WEATHER to know if these work steps can be started or not or their productivity is reduced or remained.

3.3 Simulation concept

After collecting all necessary input data, modeling the construction process and integrating the impact of weather decisions made by WEATHER into construction process are required steps. Fig. 3 shows the main concept of the simulation model, which describes the integration of weather impact on the construction process. Thereby the impact of weather is constraint of construction process. In order to simulate the construction processes, all simulation objects such as tasks, resources, material, and equipment are represented as variables. Stringent relationships between these variables like execution sequences, resources or material requirements are defined as hard constraints. Within constraint-based approach, construction process is broken down into construction tasks. Each construction task is further decomposed into single work steps, for example, erecting a façade element is separated to single work steps such as measuring, fixing. The main STS components necessary for the modeling of construction process are represented in Fig. 3. Each component has its own responsibility and needs the specific input data. *Assembly Control* is responsible for the execution of work steps and need the information of executable ability, required resource, and assembly position of work steps; whereas *Constraint Manager* controls the execution ability of work steps by checking the fulfillment of their hard and soft constraints. *Resource and Material Administrations* generate the required workers and material of work steps.

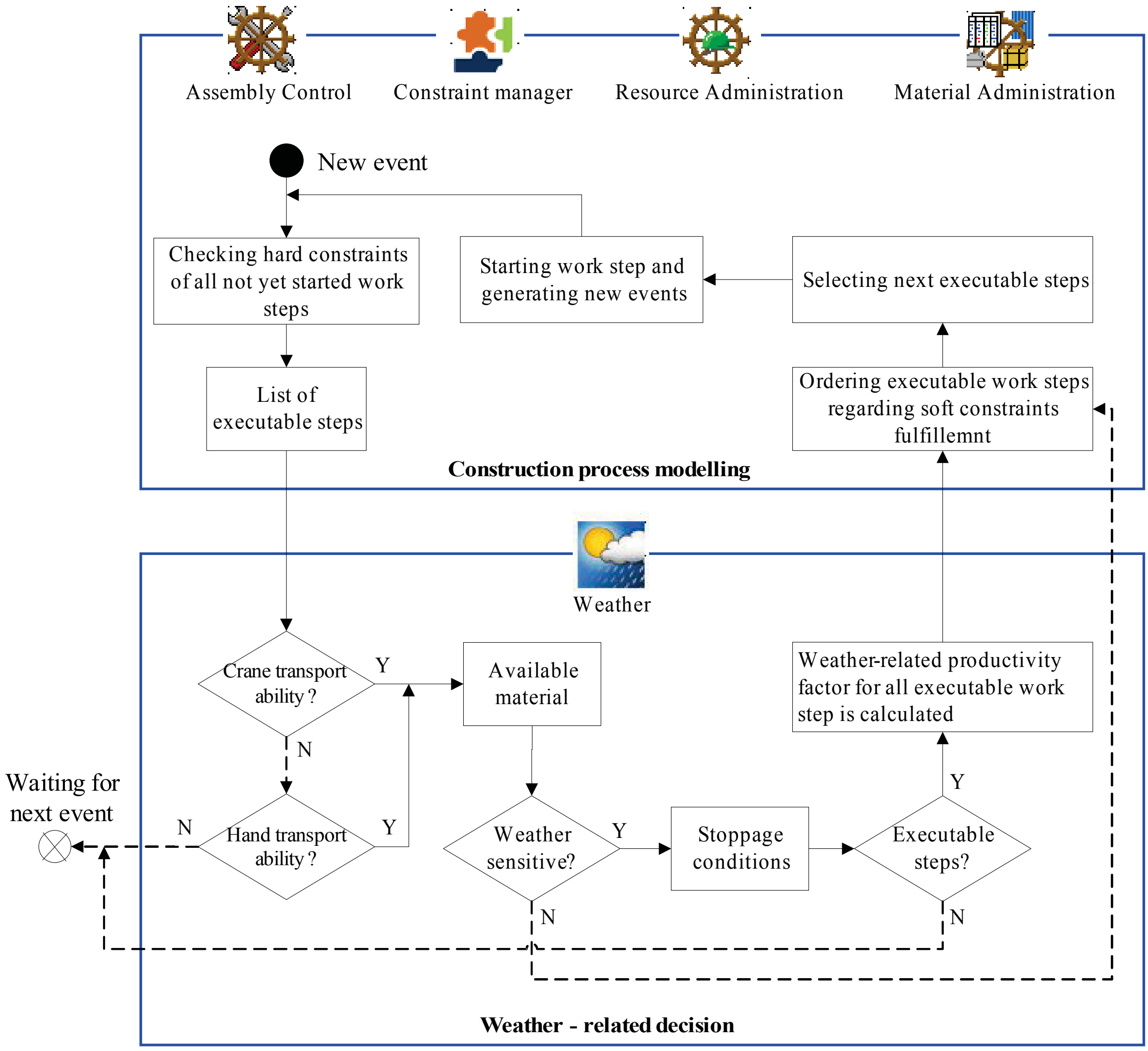

Fig. 3: Flow chart of modeling the weather impact on construction process

The interaction between WEATHER and other STS components ensures the integration of the weather effect into the modeling of construction process. If all hard constraints of work steps are fulfilled then they can be listed as executable steps. List of executable steps is transferred from *Constraint Manager* to WEATHER, where the weather impact and the decision are made. It should be reminded that, at this point of time, WEATHER generates the weather parameters based on the time given by the simulation clock. Transport activities and weather - sensitive work steps are checked for the fulfilment of the stoppage conditions. If it is fulfilled then these work steps can be started with the re-calculated labour productivity. List of these work steps and the new labour productivity will be given back to *Constraint Manager* to order and select the next started work step. These executable steps will be ordered randomly or by the percentage of the fulfilment of their soft constraints. Only the first work step in the list can be executed. In case several steps fulfil their soft constraints in equal measure, one of them is chosen randomly. After work step's execution duration is expired, work step is understood as finished and the new list of executable steps is again generated. The simulation runs until there are no more unfinished work steps.

4. Weather-related construction Strategies

Until now, modern simulation tools for the optimization of construction processes have predominantly been used only in the preliminary phase of a project. However, projects are often affected by unscheduled constraints that leads to the schedules deviation and the demand to find solutions, especially in the executing phase (Bargstädt and Ailland 2009). Adverse weather conditions are kind of unscheduled constraints, which should be updated during the execution processes. What managers should do to reduce the impact of weather to maintain the high productivity or reduce non - working time on site? In construction practice, execution strategies are manually applied in daily work planning in order to avoid additional works or disturbances. Weather – related construction strategies are defined as the selection and implementation of task execution sequences regarding to the impact of bad weather events to avoid the disturbances and reduce the non – working time or unproductive time.

The constraint-based approach used in this model is implemented to check the fulfillment of task associated constraints and to select the next executable tasks. Based on this information a variety of schedules are generated. The simulation model enables schedulers to run experiments and what - if scenarios, hence schedulers can test a variety of possible solutions to get a practicable schedule. It is possible to check for not only the strategy given by past experience but also the new possible sequences. Monte Carlo simulation techniques are possible in the simulation model to generate execution schedules; hence a multiple of simulation runs can be performed to get a significant set of solutions that can be evaluated afterwards (Wu et al. 2009).

Normally, in the planning stage, schedulers account for weather impact by proposing a variety of methods (Smith and Hancher 1989):

- Limit the available work days based on experience
- Estimate additional time to total duration
- Add a percentage of time to activities based on time of year and type of activities
- Insert one or more specific activities to schedule and name as weather delays. These activities might be added to activity chains that contain weather-dependent activities.

These methods are proposed as the acceptance of weather – related delays and are often based on the scheduler's experience and historical weather data. However the variation of weather conditions is complex, the methods applied in planning stage are not enough for avoiding consequences. Therefore, during the executing stage, the controlling of daily schedule is important whenever bad weather conditions occur. This simulation model gives schedulers opportunities to control the work steps sequence regarding to the sensitivity of work steps to weather events and the weather impact. Especially when the weather sensitive work steps are non-critical work step then the execution order of these work steps can be more flexibly control. In WEATHER dialog box (see Fig. 2), a *Controlling* tab is available for users to assign their strategies to solve the encountered weather problem. The control of the execution priority of work steps can be described as a collection of if-then rules. For example, considering the façade construction process, if it rains and there is a covered place then cutting façade elements can be executed; if wind velocity is strong then working in high level is not save but working in low level is acceptable or if it is wet then wet non – sensitive work steps should be executed before wet - sensitive ones. Hence a collection of if-then rules can be estimated for controlling the start of work steps, which is understood as soft constraints of work steps. Soft constraints represent conditions derived from execution strategies. When selecting the next start work step, the Constraint Manager takes soft constraints into account by ranking all executable work steps based on their fulfillment degree of soft constraints. Absolute compliance is not necessary, but they will make schedule generation more realistic (Wu et al. 2009). By providing and experimenting a collection of what – if scenarios, schedulers can achieve a variety of schedules and decide the best one according to their goal. This model supports schedulers in reducing the disturbances caused by weather; hence the total construction delays or cost overrun can be reduced or eliminated.

5. Conclusion

Weather clearly has a major impact on construction processes, leading to the extension of construction duration and cost overruns. Especially in the executing stage, the unexpected bad weather event is one of reasons to cause the deviation of schedule leading to the weather – related construction claims. Reducing the disturbances caused by bad weather during the execution processes is normally based on the managers' experience. The need to have a supported tool to know how unexpected weather conditions can affect the execution processes as well as how to reduce the consequences is obvious. Because of its efficiency and flexibility in modeling construction processes, simulation was chosen as the main tool to develop the proposed framework. The main concept and the required information for the model were outlined, enabling construction managers to apply the model in order to solve encountered weather problems. The WEATHER dialog was developed with a well – structured interface, making it easily to be interacted, where the weather – impact decisions relating to the presented three cases of weather impact are made. By using this simulation model, the effects of weather conditions on operative execution schedules and the strategies to reduce its consequences can be flexibly investigated. Different strategies can be experimented by using a collection of if – then rules to resolve or reduce the possible consequences due to unexpected bad weather conditions in the short term execution duration, which obviously affects the whole construction time. Besides, this approach concentrated on the performance of construction process by dividing it to small work steps, making the impact of weather on construction activities more precisely.

The next research steps may focus on the analysis of the performance time on site to support in utilizing resource in order to reduce non-working or unproductive working time on construction sites during bad weather condition time. If there are some projects are executed simultaneously at different regions by the same company, then the assigning of workers to other construction sites when encountering bad weather conditions can be a solution for effective utilization of manpower.

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THE VIRTUAL BUILDING SIMULATOR:
A POST-PARAMETRIC SPATIAL PLANNING ENVIRONMENT

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ABSTRACT: *At the beginning of the 21st century the German and European construction industry is facing vast challenges. In future, rapid technological developments and continuously increasing requirements to buildings and architecture will cause significant changes in all areas of the value chain in the construction sector. This development will also include changes in design and construction processes that will affect a building's entire life cycle.*
The growing use of digital systems allows the creation of new approaches to manage processes of unprecedented complexity. From this, new forms of co-operation emerge among the parties involved, enhanced by e.g. improved communication, interfaces in the value chain, and any logistic processes associated. Other sectors have already sketched the future, introducing new options also for the construction industry by innovation transfer. First promising results of this approach can be discerned e.g. with Building Information Modelling (BIM) on the basis of 3D building models within the frame of various research projects and first pilot realizations in practical construction.
The described research of Fraunhofer IAO and AEDAS|R&D examines the potential of post-parametric computational design together with immersive methods like Virtual Reality. The industrial approach of front-loading identifies the early design stage as crucial for all subsequent processes and the overall sustainability of future building projects. There VR together with innovative planning simulation methods allow to manage building models as complex systems for long-term planning reliability from construction to building operation.
The resulting Virtual Building Simulator represents a prototype of a design platform where the designer-user can mesh via VR in the interactive spatial formation process. The process synthesizes parametric constraints with design intent and algorithmic behavioural logics.

KEYWORDS: *Parametrics, Knowledge-based Processes, Algorithmic Design, Spatial Planning, VRfx*

1. Building sector as key for sustainable living spaces

1.1 Challenges and Potential

1.1.1 Energy, environment, resources and social change

"Since 2007 as many people live in cities as on the country" [bpb, 2007], about 3.4 billion people are concentrated on ca. one percent of the earth's surface, they consume 75 percent of the world´s energy use and produce 80 percent of the greenhouse gas [Siemens AG, 2009]. Until 2050 the world's population will increase to 9.3 billion and the cities' population will double to 6.8 billion [UN Population Division, 2011]. In the perspective of an increasing population and a shortage of resources, a rethinking in handling energy and resources is vital. From the energy consumption in cities households need up to 30 percent, 80 percent of which is utilized only for heating or cooling [AGEB, 2011]. The climate target of the German government until 2020 is a decrease of 40 percent of the energy usage in respect to the basis year 1990 [BMU, 2009]. This means that the energy consumption of buildings has to be reduced dramatically. Therefore the optimization and reduction process may not be limited only to the building utilization phase, but has to be expanded to the whole life cycle of the buildings, including the planning and construction phase. This leads to the need for new, dynamic and more precise planning and assembling methods, as well for a more sensible handling with new high-tech materials and for enhanced handling of traditional building resources and low-tech materials. The future built environment in Europe has to face the demographical change and an aging society. Therefore buildings will have to be highly customized but also very flexible and adaptable in case of conversion.

1.1.2 Processes and Tools

The building industry, compared to other sectors (for example the automotive or shipbuilding industry), is badly positioned. In many areas, especially in little planning units and SME´s, a good portion of planning development is still done with 2D drawings and static schedules. Only large planning departments and companies and/or experts work with newer planning and manufacture procedures where they can manage large-scale construction projects with increased complexity. Despite the sequential processes most of the time there is a late integration of know-how in a strictly sequential planning process. This is often caused by inadequate communication between the stakeholders in the process chain. In many sectors every specialist works on his own (schedule) and communicates only with the planner who must merge all emerging data. This often indicates a high information loss also in terms of digital planning data.

1.2 Consequences for Process and Product

Conventional Methods for construction and production processes have an insufficient efficiency as a result. Furthermore, at a certain point in the planning stage or the construction process cost and time increase in an enormous way. Through an unviable transparency, even the integration of the building owner is difficult. In addition to this, there is a lack of acceptable and reliable cost and planning reliability over the whole process. As a result the owner, in comparison to the other industries, tends to receive products with insufficient ecological and economical quality. In conclusion one can say that the potential of the building industry as a key industry for sustainable development in future is not utilized today; the industry is in need of an essential paradigm shift in planning and construction principles.

1.3 Current Approaches

Nowadays the current solution statement is the application of virtual project spaces or project communication platforms which enable an exchange of relevant planning data through internet for stakeholders in the project. So, either at the same time or in succession, multiple users can access to confidential or relevant planning data. In these secured spaces you can always find the updated/new data, furthermore user access and transaction will be registered and documented in order to guarantee a full documentation. A similar approach is offered by the Building Information Modeling (BIM), where all schedulers work in one holistic model [Günthner, Borrmann, 2011] and every specialist receives only the data that is relevant for him. This method guarantees precise work without loss of information and additional cost for architecture. In the model there will be attached object lists and basic computations which are collected in real-time; in this way model changes in one building part will lead to an update of all quantity calculations. In addition most BIM's applications can identify collisions in the model which can then be corrected after simulation. In most cases BIM can work directly in a 3D model which can also be presented in a Virtual Reality (VR) environment. In the VR different stakeholders or the owner enters the 3D model via a

CAVE or a Powerwall and can move freely in the virtual space. Impressions, illuminations or layout schemes of the building can be simulated and evaluated close to a realistic experience in order to make future-proof planning decisions where it is possible.

2. New Construction Processes through post-parametric Planning Methods

2.1 Innovation Networks for Synchronization of Stakeholders

In order to change and optimize planning and construction processes in the long run, it is of fundamental importance to continuously examine the whole value chain from the first design to the final realization. In order to pursue the approach of a holistic and fully-integrated planning in construction industry, the Fraunhofer-Institute for Industrial Engineering (IAO) has launched the innovation network FUCON (Future Construction). In this joint research project Fraunhofer IAO develops in cooperation with renowned partner companies in the building and construction industry new concepts of construction methods and strategies for a more efficient and future-oriented value chain for construction. The main objective of the joint project in industrial and applied research is to establish a partnership network as a multi-disciplinary platform for discussion and innovation in order to promote the rich knowledge existing in the industry sector through the interdisciplinary cooperation. One of the main interests is the realization of prototypes to implement and evaluate innovative approaches that later will be used in real building projects ("proof of concept").

2.2 Concept and Vision for Construction in 2020

2.2.1 Target and scientific Approach

The scientific basis for the development of the Virtual Building Simulator was the common definition of a strategic objective for construction in the future. The preliminary research question was: How will the construction processes look like in the year 2020 if the right decisions for sustainable buildings and construction processes have been made today? Starting from this question the crucial goals for the involved companies and also the construction industry itself were defined as follows: sustainable efficiency improvements and cost reductions throughout the entire building life cycle, quality improvement in operation by optimizing the interfaces, a more flexible and faster project execution of construction work through a lean construction approach, increasing energy efficiency in construction and buildings and accelerated product and process innovation cycles to speed up the implementation of sustainability goals. The scope of the joint project FUCON is to actively face this general vision of a future-oriented construction industry, and to realize a comprehensive process scenario that can pinpoint and provide new measures and approaches for the construction industry. Because of the complexity of current planning processes in construction and the interrelated innovation barriers, conventional methods of forecasting and trend extrapolation do not offer goal-oriented conclusions on complex issues like the future development of different technologies and the organization processes of connected values.

The scientific approach of scenario development by Gausemeier is a dedicated method of foresight that enables the simultaneous oberservation and discussion of different phases or key factors of the value chain structure in construction with the goal of a comprehensive redesign of traditional processes which still shows a strong sequential planning and construction implementation as mentioned above [Gausemeier, Fink et al, 1996]. In this phase, experts from different sciences and the industry were participating in the innovation network FUCON, which thanks to these broad competences allowed a thoroughly analysis of the whole planning and construction process

2.2.2 Scenario Development „Parametric Age 2020“

One of the technology scenarios that were developed is titled "Parametric Age 2020 - Individualized Building for highest customer and environmental requirements through innovative processes." Technical points for solving the previously identified challenges are to fully digitize the information flows, as well as the deep parameterization of planning and process models, a highly-customized manufacturing through automation in the pre-fabrication and finally a high degree of process optimization through Lean Construction approaches [Krause, Braun, 2009].

Despite individual innovative technologies, the current planning process are still dominated by a high complexity in all planning stages. Each building will be unique and individual architecture is associated with high costs and high effort. The construction industry in 2020 will however provide technological and procedural innovations in buildings that were previously not feasible in a conventional manner and will also ensure an optimized design, high resource efficiency, excellent amenity values and high sustainability. Integrated planning will be required for new and streamlined guidelines in order to improve the co-operation between companies; this will also lead to changes in the previous inflexible regulation system. This common challenge will unite the industry's efforts and will create new opportunities and business models. The intelligent combination of innovative developments in the field of manufacturing, planning and construction will develop a high automation of the entire process chain. The digital value chain will eliminate interface problems stabilizing the flow of constant information and with this effect, physical simulations and building information modeling (BIM) can be fully integrated in the early stages of the project planning stage. These new systems will provide the project manager with additional information about the behavior of future building in terms of resource consumption, life cycle management, product properties etc. The parameterization of requirements and digitalization of the process chain allow the redesign of the entire planning process and will enable designers and companies, along with standardized but customizable manufacturing processes, to produce buildings for different user requirements and needs without limitations. The growing demand for high-quality real estate, optimized in terms of quality of life, energy efficiency, user comfort, sustainability and other aspects can then be planned, implemented and realized. The frontloading of information from manufacturing equipment such as machinery, tools and material properties into the early design stage as well as a high level of industrialization granted by robotics, laser-cutting and CNC machines can have a powerful impact and positive economic effects on the entire life cycle of buildings.

By such a networked and digital process chain with integrated parametric design and industrialized manufacturing, sustainability can be promoted in all its aspects, since all known environmental effects of planning are known at the start and can be modified accordingly.

2.3 Post-parametric (knowledge-based) Design as Construction Principle

According to described scientific approach the principle of post-parametric planning groups buildings as systems with many interrelated planning values. These values exceed the geometric modelling of single components. All information levels ranging from material attributes to assembly standards, up to the urban context are thereby connected so that changes of one parameter affects other dependent model areas. The early integration of assembly, execution and application parameters offers the possibility to generate and visually check different blueprint versions with the knowledge of highly producible and feasibility of single construction elements. Therefore, it is possible to modify attributes of the digital building model according to the preferred requirements. This Approach avoids unforeseeable cost increases or a deviation of predefined planning goals. The digitalisation of planning and construction processes also shows high potential in the early integration and consolidation of user requirements as the future building users. It also implements this expertise in form of variable parameters and fixed framework constraints in order to fulfill the previously shown vision of a fully digitalized added value process and a sustainable building life cycle.

The documentation and evaluation of relevant influencing variables is performed through parameter catalogues which contain quantitative information about manufacturing capacities, architectural knowledge, planning performance indicators and research results as well as qualitative information in form of parameters, expert estimates and empirical values as referential constraints and target values.

An example can be shown by means of the facade as a subsystem of a building: The information or parameters for a facade planning which play a role in post-parametric planning are not precise geometric measurements of single components as e.g. in Building Information Modelling (BIM), but material systems consisting of fabrication capacities of the respective production facilities and corresponding material attributes. This includes on the one hand a maximum of assembly tolerances in respect to width and length, a maximal bending radius or processable material thickness. On the other hand physical material attributes such as E-Module or stiffness are taken into account since these attributes are strongly linked with each other in the development and production of components.

If within the next decade a more organic or ecologically sensitive architectural language is implemented in our cbuilt environment it will have a great influence on the necessary individualisation of construction components and products. The subdivision of a 3D-curved facade surface can be separated into manageable thus feasible (in terms of production) single components which makes it necessary to produce a multitude of similar but differently shaped parts within a manufacturing plant. The earlier these material attributes and assembly capacities are integrated in the design stage, the more efficient and precise the result will be at the end.

Hence, post-parametrics as a scientific construction principle describes digital and consistent information chains which gather all relevant information for the life cycle of a building (from planning over construction to conversion or adaptation) and integrate them in the early design stage with the goal of a long-term planning reliability.

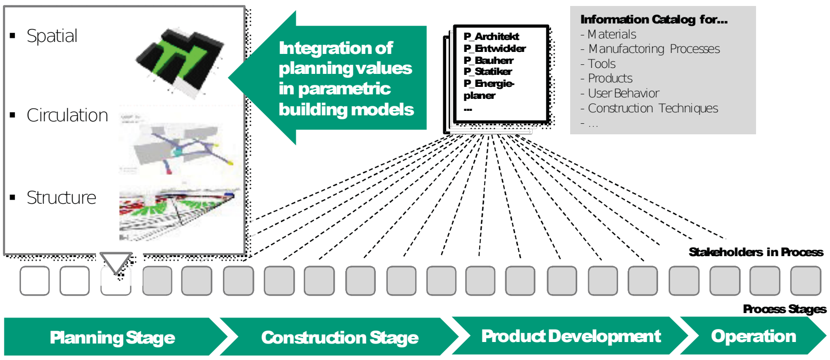

Fig. 1: Approach of the VBS: Frontloading of Information through Post-parametric Design and Virtual Reality

3. The Virtual Building Simulator: a prototype of algorithmic immersion

3.1 Design Brief Development

The initial brief of the Virtual Building Simulator (VBS) as a demonstrator was based on a parametric workflow that is slowly gaining ground in the industry. This model represents a type of automation of a linear construction sequence where parameters are declared and constrained then executed and the results evaluated (the old 'generate and test' approach [Mitchell, 1990]). The brief was extended to allow for simultaneous design simulation with integrated evaluation, based on quantitative limits and a minimum setup of parametric associations. The matrix of associations and quantities should always be adaptable by the user and the algorithms according to the state of the simulation. This user-algorithm dialogue represents a explorative negotiation of the design space in real time.

Where standard parametric construction sequences are appropriate for geometric structures and surfaces, it is our belief that parallel computing is appropriate for topological and combinatorial issues such as configurations of space. Hence, the brief was re-interpreted to focus on the generation of spatial configurations and therefore on the designing as algorithmic simulation. While not all stages and aspects of the design process for spatial configurations could be covered in the given time, three aspects of the spatial planning workflow were chosen for development: site condition and envelope, building mass and floor layout with structure. Initially, it was proposed to pass configuration states as data between the simulations directly, but later decided to attempt a perceptive link between the applications instead by virtue of the design aspects the simulations addressed. This would still allow the user to understand a progression through the design space based on behavioural parameters and performances and reduced the risk to spending too much time on the I/O alignment.

It represents good design practice to evolve a coherent design language and spatial structure across scales in order to enable the user to recognize relationships between spatial aspects that create a sensation of continuity of experience and spatial organization [Norberg-Schulz, 1965]. This can be done formally and on the level of the logic of organizing space via models of behaviours. In order to organize the spatial configurations not only on parametric constraints but also on some design intent of organizing logic, movement and access patterns were chosen to represent the organizing algorithms. Therefore, not only a dialogue between user and algorithms but also a negotiation between quantitative input like development program, qualitative performances like good circulation patterns (their evaluation criteria are described below) and design constraints like layout adjacencies is facilitated.

The simulation models reflect a Modernist organic approach to architectural design (such as Frank Lloyd Wright) to evolve the spatial configurations from 'inside out'. This has recently been demonstrated non-computationally by designs such as Office dA's Issam Fares Institute or of course older examples like Hertzberger's office designs. Algorithms that model the logic of movement structures were based on Frei Otto's analog route bundling models [Otto and Rasch, 1995] or the concepts of centrality discussed in geography as early as Walter Christaller's Central Place theory [Christaller, 1933]. It is paramount for us that the algorithms correlate to the models of intended design logic in order to create a perceptive identification with the simulation dynamics and the resulting spatial organizations correspond to the behavioural conditions emerging from the simulations. Equally, creating an algorithmic consistency across design aspects allows for the above mentioned organizational continuity of space across scales.

The visualization and interaction via the Fraunhofer IAO's VRfx virtual environment represents a further extension of the idea of consistency of models. Not only are the simulations developed through a correlation of design intention, spatial organization logic and algorithmic models but also the Human-Computer Interface (HMI) was set up to approximate the notion of movement by tracking the user-designer via a handheld tablet computer as he can navigate through the simultaneously configuring spatial organization. Finally, to support the explorative negotiation where design states can be simultaneously generated while evaluating via spatial analysis or other techniques, it is advantageous to be able to allow the user-designer to be situated inside the simulated spatial configuration to inspect qualities or phenomena difficult to encode analytically. A novel type of algorithmic immersion is produced.

3.2 Objective

It is becoming clear that the changes imposed by algorithmic design influence the working process of the architect and designer, a shift from working with digital drawings, 2D and 3D CAD, to working with systems, parametric descriptions and code. What is sometimes overlooked is that the means used for design also determine how the architect communicates and collaborates with other stakeholders. In algorithmic design the focus is shifted from working with a concrete design proposal to authoring systems that afford ranges of possible design outcomes. These systems can be designed with user interaction which opens up the design explorations to a wider audience. Even in the case of a traditional design process a number of alternatives are often developed, which one can argue, also constitutes a design space. The difference is that new solutions in this design space can only be explored through drawing or sketching alternatives, while in the case of algorithmic design the possible variations can be generated by any user willing to engage with the system. When working with algorithmic design the process is thus split into two separate design activities: designing the algorithmic systems and exploring that system interactively.

One of the principal ideas behind the VBS was then to combine the algorithmic and participatory approach of CDR with the immersive and interactive VR systems of Fraunhofer IAO, into a system that could facilitate dialogues and interaction between the stakeholders. Earlier interactive VR systems have been used to communicate and discuss architectural design proposals; these projects focus on allowing the client to understand the spatial and material aspects as close as possible to how the building is to be realised. Kitchen [2007] describes how a VR system can be used to reduce miscommunication and misunderstandings between the architect and the client. The current research is aimed towards systems that allow multiple stakeholders with various backgrounds to collaborate on a given design. The work is related to what is referred to as charrettes in planning and urban design, where residents, municipal officers and urban planners and developers work together to come up with solutions that satisfy the requirements of many different groups. For the demonstrator this means that emphasis is shifted from presenting the end user with a finished building proposal that they can inspect, to facilitate stakeholder decisions to be embedded in the generative process by situating the user within the virtual algorithmic space of formation. The stakeholder is thus enabled to respond to conditions in development and negotiate aspects of the building while still in diagrammatic states [Derix, Gamlesæter et al, 2011].

3.3 Computational Design Models

As a case study for developing the algorithmic systems a lab building typology, more specifically a private research institution program situated in Germany, was selected. The research lab became the point of departure for the exploration of three levels of adjacent concerns in the design process: site massing and envelope, circulation and common areas, workspaces and structure. Each of the three levels results in an algorithmic system with a user interface and VR link for interactive investigation of designs addressing the two concerns and their interdependence.

The site massing and envelope exploration allows the user to place different parts of the development program on site such as green spaces, parking, built volume and get feedback on how the current distribution matches the area schedule, as well as a proposed massing and skin articulation. The input to this stage is an area schedule description of the main parts of the program. The aim of this stage is to be able to visualise the development program three-dimensionally on the site, and at the same time understand the envelope formed by a certain distribution. The system allows the user to manipulate how the development program is laid out on the site, both in terms of manipulating the underlying grid, but also to determine which programmatic use should be associated with each grid cell. The granularity of the grid can be set via sliders and the end point of each grid line can be dragged as long as the integrity of the grid is kept intact (i.e. each grid line does not cross any of the two neighbouring lines). In this setup the generation of the shape of the envelope follows from the organisation and size of its parts, i.e. the user configures the parts of the building, and the system itself has a built-in strategy for how to make this configuration three-dimensional, and how to articulate the façade with open and closed panels.

Fig. 2: Diagrams showing massing and envelope from the first application

The second system looks at the relation between circulation and the common areas in the building, and the connection to the research departments and specialized labs and offices. It has been argued that the internal organisation of research labs influence the performance of the research teams working there. In his book Space is the Machine Bill Hiller compares the layout of two research institutes and observes how the two different layouts results in varying degree of inter-departmental communication [Hillier, 2007]. It was in view of the relationship between movement, communication, and performance of a research institute that the current work on internal organisation and circulation was carried out. In the implemented system the internal room program is divided into common areas (café, library, main circulation spaces) and private, more specialised areas such as lab and offices. The stakeholder can manipulate the internal configuration and see how it affects circulation in the building. The aesthetic expression of the building was also driven by the interplay of the two types of program; Common areas and specialised areas got their own distinct expression and logic by defining the building as a solid block onto which the common areas are formed by carving out voids.

Fig. 3: Diagrams showing circulation and massing from the second application

The third exploration is used to negotiate the relation between workspaces, such as labs, offices and access areas, and their relation to daylight, structural elements, and internal circulation. This model works on a smaller part of a layout, only one floor, and considers the internal logic of that part. The basic principle is to create a landscape of columns, light shafts, room dividers and furniture by setting up certain relationships between these elements. The user affects the internal layout by moving centre points of programmatic elements (e.g. labs, office desks, meeting area). From these centre points the plane is divided into triangular regions using a Delaunay triangulation [Delaunay, 1934], and each triangle holds a structural element either a conventional column or a light shaft that lets in daylight. Interior design components, such as walls, chairs, and desks, associated with each point clusters into the adjacent triangles of the centre point. These components are placed according to predefined parameters. The internal circulation, paths for movement between each of the points, is also visualized, and part of the internal configuration.

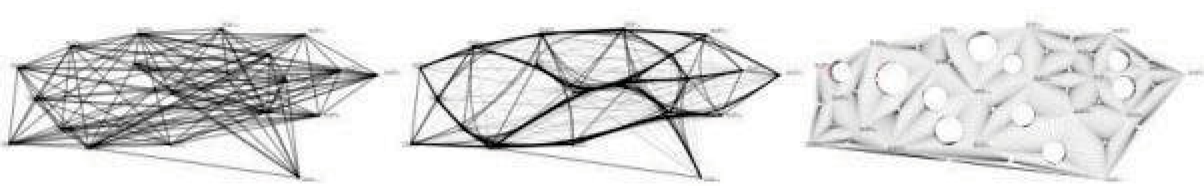

Fig. 4: Diagrams showing adjacencies, circulation and structure from the third application

The VBS aims to demonstrate algorithmic consistency where the understanding of the processes creates insights into the interdependence of related but distinct design aspects. For example massing and envelope application both the site and skin is constructed through what is referred to in Computational Geometry [O'Rourke, 1998] as an arrangement of lines, where a number of lines split the plane into a set of convex polygons, in the case of the skin the arrangement works in 3D, as if it was unfolded. Similarly a force directed bundling algorithm [Otto, 1995] is applied in generating both the three dimensional circulation and organizing the workspaces on a more detailed level on a two dimensional floor. As in the first applications, the basic algorithm of the second and third applications remains conceptually the same but working under different constraints.

3.4 Technical realisation

3.4.1 System Overview

To take advantage of the collaborative synergy of the two partners with different domain-specific expertise we have split the application in an application server and a view client, and conceived a lightweight protocol which protects the architectural experts from being bothered with VR specific details and keeps the VR system scalable, customizable and independent from the architectural application logic.

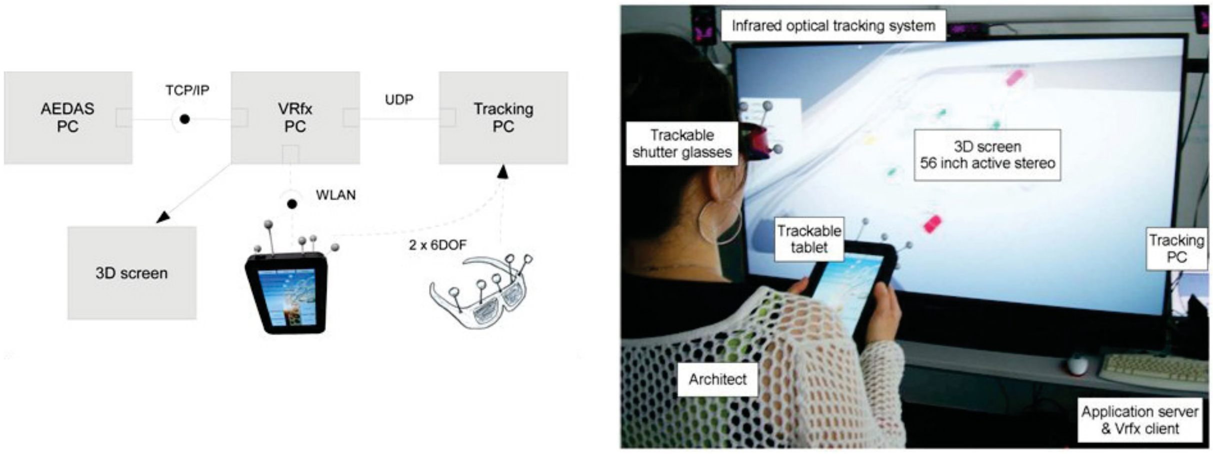

Fig. 5: Hardware components and technical setup of the VBS as presented at BAU 2011 in Munich

3.4.2 Protocol and Shared Primitives

The view client presents three configurable virtual devices to the application via the protocol, the graphics view, the parameter manipulator and the application control device. The parameter manipulator is a generic device which is used to interact with the model parameters. The graphics view displays 3D polygonal data and 2D data at a virtual head-up display. It also sends events if the user selects or drags an object in the scene.

Due to the generative logic of the models, the shape and layout proposal are not composed of a set of building modules, but formed by algorithms where the topology of the geometry is constantly changing. Therefore in the protocol we use low level polygonal geometry representation instead of higher level objects. Furthermore, by focussing on low level primitives the system lends itself to many types of visualisation, from diagrammatic line drawings to more realistic representations of a building proposal.

The application can send operations (construct, modify, delete, set), which contain an object for example a visual or a material. A visual itself contains a transformation, a geometry instance and refers to a material. A visual can be attached to the world coordinate system or to a virtual head-up display (HUD) and can be tagged to be a billboard (always facing the user), which is useful for text visuals. Available geometry types are:

- Meshes: a list of vertices with optional normals, colours and texture coordinates.
- Lines: a list of vertices which can be interpreted a line segments or a connected line, vertex colours allow colour gradients
- Bsplines: similar to connected lines, vertices are interpreted as Bézier-spline
- Points: a list of positions, size and colour is adjustable
- Text: displays a string, colour, font, alignment is adjustable, can be marked to be a billboard

For user interaction with the 3D model the view device can send drag and select events via the protocol. The events contain an object id and a ray. We do no ray intersection on the view side but let the application side interpret the ray by itself. This is due to not restrict the interaction variants and to allow to intersect with the procedural model instead of the polygonal model.

3.4.3 HMI

One of the main challenges in this project was to integrate the multiple interaction paradigms which are necessary to handle as well the interaction with the parametrical model as the navigation in various views. To do this we use a tablet computer with Android operating system and multi touch display. The tablet is multifunctional, and enables the user to control the application, to manipulate the model parameters and to navigate through different visual representations of the application model. The tablet has attached markers and is tracked by an infrared optical tracking system. In this way the tablet computer functions also as an absolute 6 DOF input device.

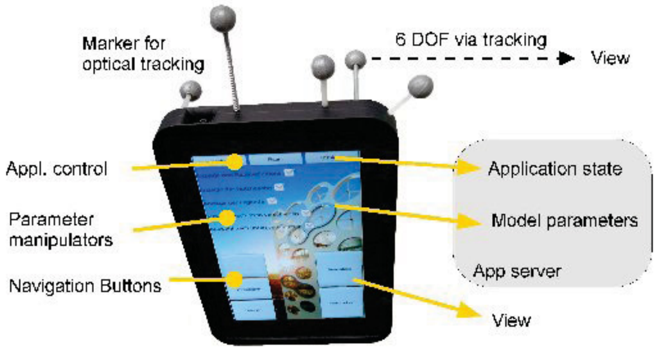

Fig. 7: Tablet PC as a hybrid input device

On the tablet runs a java program which implements the client side of the protocol. It is divided into three modules each with a visual representation on the touch screen:

- The application control section, which contains the buttons to start modules and load/save sessions. It is configurable and is directly presented to the server as the virtual application control device.
- The parameter manipulator section which contains manipulators for modifying the model parameters. This section is configurable by the server via a list of parameter descriptions. This section is presented to the server as the virtual parameter manipulator device.
- The navigation section contains buttons which are listenable by a VRfx plug-in via a protocol. The VRfx plug-in then will combine the button states with the 6 DOF tablet location and the head location from the tracking system to place the cameras of the 3D view.

The navigation model is very similar to the usage of a prop as described in [Hinckley, Pausch et al, 1994] and has proven as intuitive. Changing the position and orientation of the tablet will change the position and orientation of the scene proportionally, where the centre of rotation is connected fix to the scene coordinates.

For direct interaction with the parametric model in the virtual environment, the tablet can also function as a pointing device; we use the ray metaphor and buttons at the touch screen for selecting and dragging objects. The ray starts from the tablet and changes its orientation accordingly to the orientation of the tablet and is visually represented by a line in the virtual environment.

4. Conclusion and Outlook

While it is obvious that several iterations would be necessary to make the step from demonstrating a principle to implementing a new workflow in developing a full architectural design proposal, the current demonstrator should be regarded as a first step towards such integration.

VR in the context of algorithmic production for spatial configuration could offer a particular value as the emphasis for spatial planning lies with occupational performance, which relies on cognitive features of shape. If the formation of spatial configurations can be interacted with from within, tacit qualitative knowledge about building spaces could be integrated more fluently into the design process without having to make reductive assumptions about qualities of space to evaluate with afterwards.

5. Acknowledgments

We would like to mention Pablo Miranda who formed part of the Computational Design Research group of Aedas|R&D for the design and development of VBS. Also we would like to thank Arnold Walz for the inspiring conversation about the abolition of the distinction between space and structure as it occurs generally in building construction. The notion of load-bearing walls we discussed that do away with the separation of usable space, i.e. slabs and structure such as columns or structural walls, is very consistent with the concept of algorithmic consistency or the mapping of computational models into spatial logic. Equally, we would like to thank Günter Wenzel of the IAO for his participation in the debate and briefing of the immersive system and Matthias Bues of the IAO for his help on the development of the HMI and protocol for the VRfx system.

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DEVELOPING A TOOLCHAIN FOR PROVIDING AUTOMATICALLY HIGHLY ACCURATE 3D DATABASES

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ABSTRACT: *The usage of databases containing 3D information is getting more and more importance in various domains like traffic management, urban construction, simulation of safety critical driver assistance systems etc. Nevertheless current approaches do not tap the full potential of such databases. Most of them are set up by hand and do only contain data suitable for one main purpose. In this paper a tool chain approach is presented that combines automatically generation of 3D landscapes with precise real world data (like cadastral plans, road measurement, aerial photographs, navigation data, etc.) for usage in more than one field of application. This tool chain is developing by the Institute of Transportation Systems within the project called "SimWorld". SimWorld sets up a database in the domain for transportation research. Therefore it was necessary to focus on road representation in a new and very detailed way. Additionally a representation of urban environment and rural areas including high quality visualization needs to be generated out of this data. A special database schema reflects these both issues. In the following the database design and the tool chain modules will be discussed in comparison to existing approaches and explained in detail. Also the topic of the project outcome and the further development of the SimWorld tool chain will be touched on.*

KEYWORDS: *road description, precise data, urban environment, simulation*

1. Motivation

More and more people discover the potential of using large databases for generating 3D landscapes. These databases are used for e.g. visualization of cities, 3D navigation, planning of constructions etc. The core challenge here is to fill such databases automatically to avoid time consuming manual work. Hu, et. al. (2003) categorize some common approaches and describe their advantages and disadvantages. These approaches are good enough for development, planning and administration work. But they all have a lack of street level data. However this data arouses more and more interest for using it as maps in navigation devices, improving driver assistant systems or being the basis for traffic or driving simulations.

The Institute of Transportation Systems operates different driving simulators and test vehicles for conducting test trials to develop, test and evaluate innovative driving assistant systems and automation. These simulators need data for visualizing the environment and also for providing physical/emulated data for e.g. vehicle dynamics or sensors. Current databases are prepared manually and have therefore a lack of accuracy compared to the reference in the real world. With the help of more and accurate data it is possible to achieve a higher level of reality within the simulation. Therefore the institute gains a better comparability of simulation trials and field operational tests as described by Richter et. al. (2009).

2. Generating 3D Databases for Simulation

For getting more reality into the simulation the interdisciplinary project called "SimWorld" was started in 2007. Primary involved are the Institute of Transportation Systems and The German Remote Sensing Data Center. The project goal is described by Sparwasser et. al. (2007). He introduced the idea of generating virtual worlds with the help of a tool chain approach taking real world data into account. The main objective is the automated generation of 3D landscapes and logical road descriptions. These outputs will be created out of a database containing all necessary (collected) real world data. This database manages complex data to be sufficient for driving simulations and a lot more specific data than in the projects present by Hu, et. al. (2003). Therefore additional data and a different way of processing the data are needed. The implementation and enhancing of this tool chain approach is described in the following paragraphs.

2.1 APPROACH

One of the core elements of the SimWorld tool chain is the SimWorld database. Its design follows on the one hand the concept of scene graphs and on the other hand the OpenDRIVE standard for describing roads because it has to provide data to generate 3D landscapes for visualization and a logical road description for the traffic simulation.

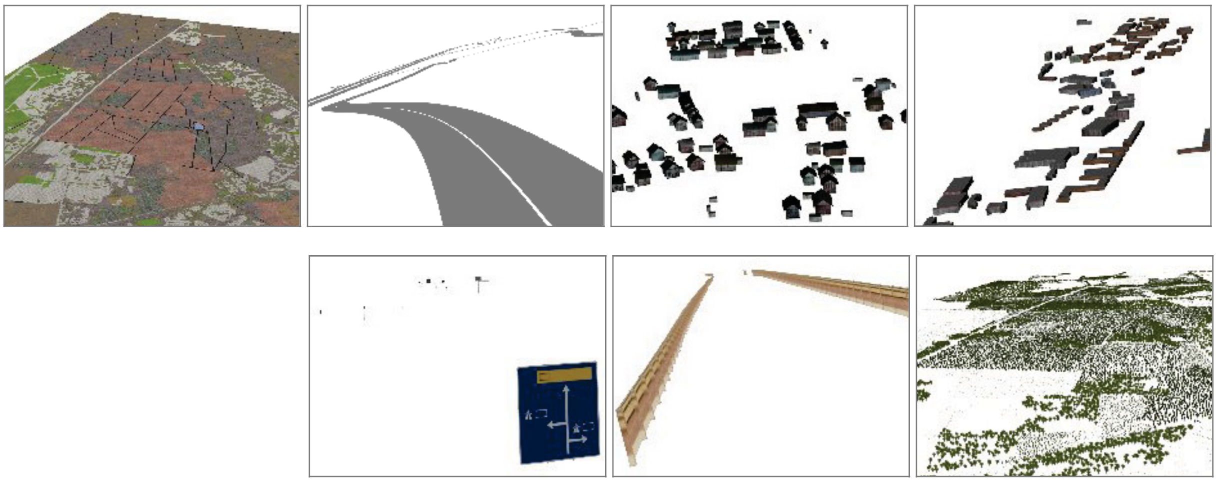

Fig. 1: Important parts of the SimWorld landscape.

The scene graph concept (well-known from the computer graphic domain) makes it easy to model virtual 3D landscapes in a database. Basically this data contains a lot of geo-coordinates. These coordinates are then enriched with further attributes to assign them to surface areas, use them as outer edge of buildings, coordinates of points of interests etc. Further logical groups like the surface or buildings are specified in more detail to distinguish their appearance. All logical groups compose the virtual landscape. The important ones are the surface with different coverage, roads, small and mid-sized residential houses as well as industrial structures, single objects like road signs, linear objects like noise barriers and different vegetation according to surface coverage. The 3D output of these logical groups is shown in Fig. 1 from top left to bottom right.

For describing roads the OpenDRIVE standard (well-known from the driving simulator domain, also used for driving dynamic tests etc.) is used. It is an open and European-wide de-facto standard for road description, developed and maintained by a core team consisting of industry companies and research institutions. Like written by Dupius et. al. (2010) in the OpenDRIVE format specification it consists of reference lines, information about the lanes (number, markings, etc.) and features like road signs, restrictions, links and user defined data. Fig. 2 shows this structure. Due to this separation of content it is possible to have on the one hand a logical road network taking e.g. linkage and numbers of lanes into account and on the other hand the description of the appearance of the road by defining width, slope, color, material etc. of lanes and markings. All these information is stored in general in form of XML elements. The SimWorld database contains such OpenDRIVE elements for generating the logical road network description and an accurate 3D model of the road.

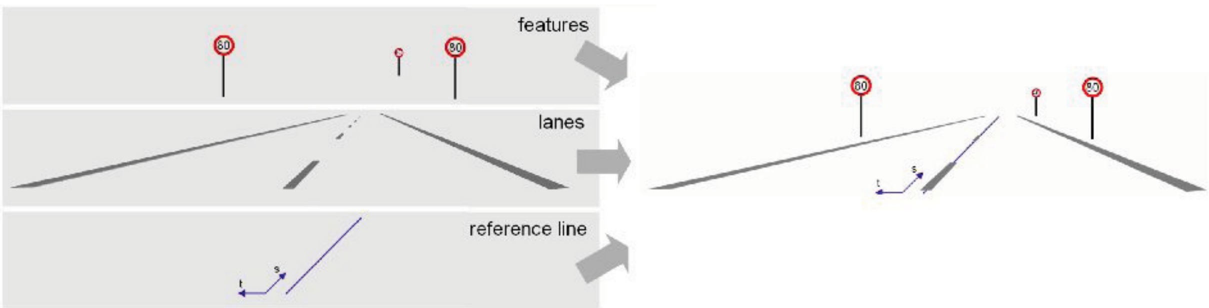

Fig. 2: Principles of road layout.

A lot of conventional data sources like e.g. cadastral plans, terrain models, satellite images, aerial photographs and navigation data are used to fill the SimWorld database. The challenge is to integrate vast heterogeneous data sources that provide a nationwide coverage so that the tool chain will work for more than one certain city or area. The heterogeneous data is transformed into the recently explained database schema. For urban areas with their complex road networks and their characteristics there is no other option than surveying the roads manually. At least cadastral data contains not all necessary data that is needed (e.g. number of lanes, precise width, etc.). To cope with this problem there was a methodology developed within SimWorld to gather all requested data and convert them without major processing into OpenDRIVE elements. This methodology based on sensing roads as graphs (enriched with attributes) and not on simple measured points without any logical relations. It is even more simply to generate 3D roads and their logical description with mathematical specifications instead of using coordinate clouds that have to be converted first and does not contain any logical information. For surveying roads as graphs it is important to have rules that work for simple and complex road scenarios. A medium complex situation is shown in Fig. 3. Thus it appears that multi lane roads with central reservation should treat as two different roads to avoid uncertainty where the mainline of one road should be located. Also the construction of paths across junctions follows some general rules like always being situated on the left so that all lanes are attached to the right (but left turn lanes are exceptions). For the most complex junctions these rules have to be verified, nevertheless they seem to work at least for the test site.

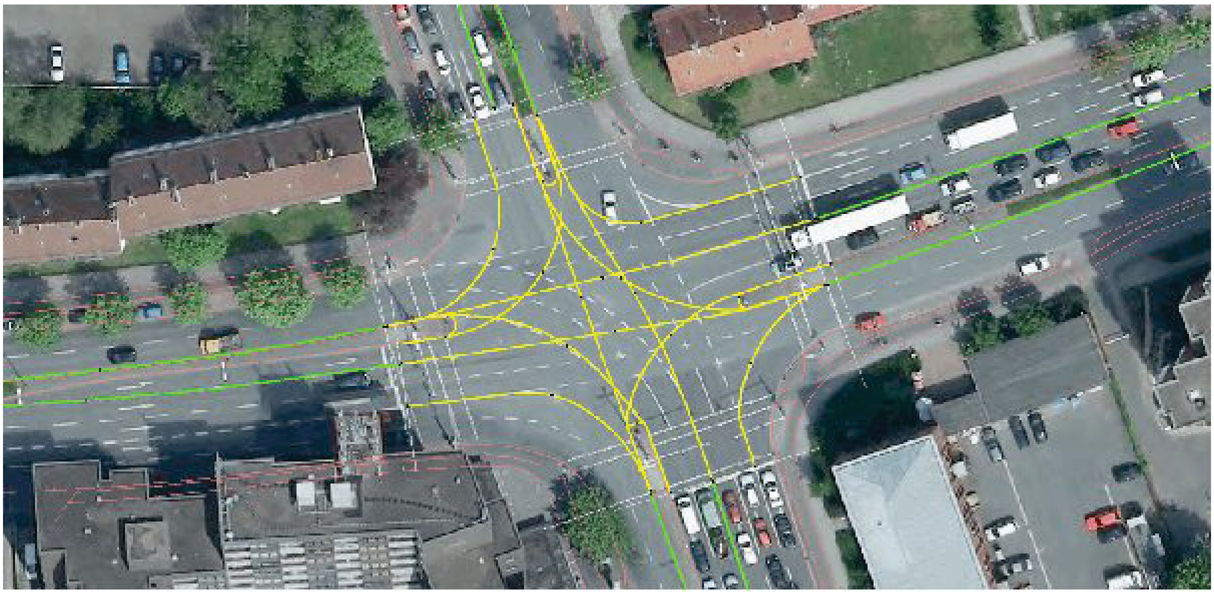

Fig. 3: Mainlines (green) and paths (yellow, within the junction area) describing the appearance of a junction.

2.2 Realization

The first phase of the SimWorld project focused on motorways and rural roads. In the current second phase SimWorld is enhanced by adding the generation of urban areas. Therefore the city of Braunschweig (population: 245,000) in Germany is the base for realization of a first prototype to develop and test the SimWorld tool chain. Lancelle and Fellner (2004) already generated a 3D city model of Braunschweig with the help of commonly available data but the data processing required a lot of manual work. The resulting city model contains only a few information about the road network that is sufficient for a bird views to get an impression. For driving simulations especially the visualization on street level has not the appearance of a city, a lot of infrastructure is missing and the textures of the buildings are quite basic and unpleasant. Therefore within SimWorld new data sources are discovered and integrated into the database.

The tool chain itself has different degrees of automation within the modules. The data import (step one) is the most difficult part. For each new data source a new importer has to be set up. Mainly this is covered by using existing GIS tools or tools under development. Sometimes in rare cases manually corrections in the data are necessary. It is worth setting up new importers if the data source has a nationwide coverage. The data post-processing (step two) works already on normalized data so that only few adaptations are required. Post-processing means e.g. classification of land coverage or generation of road elements. This is also partly done by third party tools. The outcome of the processing is inserted in the SimWorld database with its previously described schema. Based on this database currently two exporters are getting the normalized data for generating fully automatically the 3D landscape model (as also written above containing: surface, vegetation, buildings, roads, signs, noise barriers etc.) and the road network as an OpenDRIVE file (final step). Both modules are implemented in C++. For creating 3D models the OpenSceneGraph framework is used.

2.3 Result

As first demonstration an area of approximately 100 square kilometer in the northeast of Braunschweig covering a part of the motorway A2 and A39 and the motorway intersection Wolfsburg/Königslutter is completely reproduced. For that the database contains a lot different satellite and aerial data for the surface (e.g. IKONOS, SRTM, Landsat and HRSC data), data of land usage (on the one hand preprocessing of remote sensing data and on the other hand cadastral data), data for road representation (Tele Atlas and cadastral data) and finally cadastral data describing buildings. Additionally to that a lot of textures and 3D models are stored in the database, too. As touched in the previous paragraph about the realization some data has to be preprocessed before using them for the real landscape generation, terrain data is one of these cases. For the usage in a driving simulator especially the details along of the roads are important. Regions that are more distant can be represented with fewer details because they are only visible as small parts of the visualization within the simulation. One of the challenging tasks is to merge all different elevation models with their varying resolutions. Especially the decision of which data is correct and have to take into account is not trivial at locations that are covered by different sources. Fig. 4 shows the merged landscape data for the demo area as an overview screenshot. The dark areas contain a lot of more geo-coordinates in contrast to regions covering none of the roads of interest. Also the different resolutions can be figured out and the figure also shows that the landscape is tiled for a later on paging within the image generator.

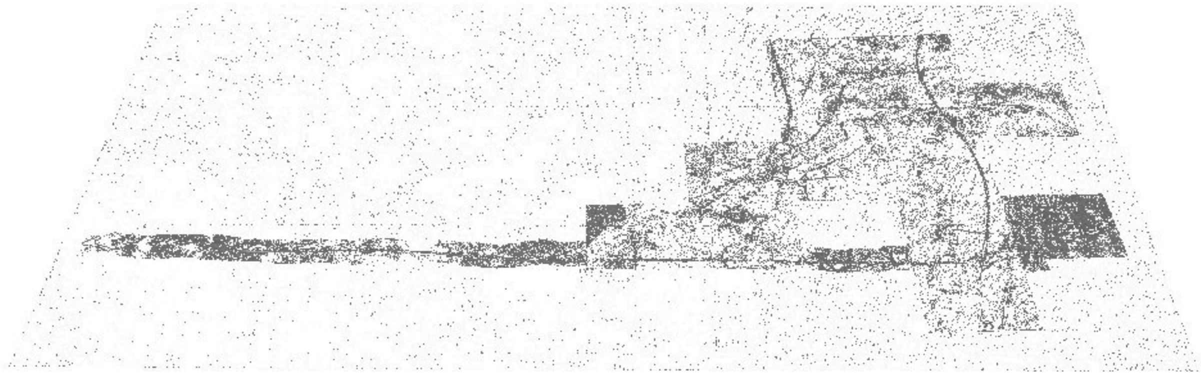

Fig. 4: Geo-coordinates of the demonstration area.

Fig. 5 shows a landscape screenshot of a freeway and business area situation including all generated parts like previously introduced and shown in Fig. 1. Weather and light effects that are necessary for driving simulators are added in real time to the scene by the image generator and therefore not shown in Fig. 5.

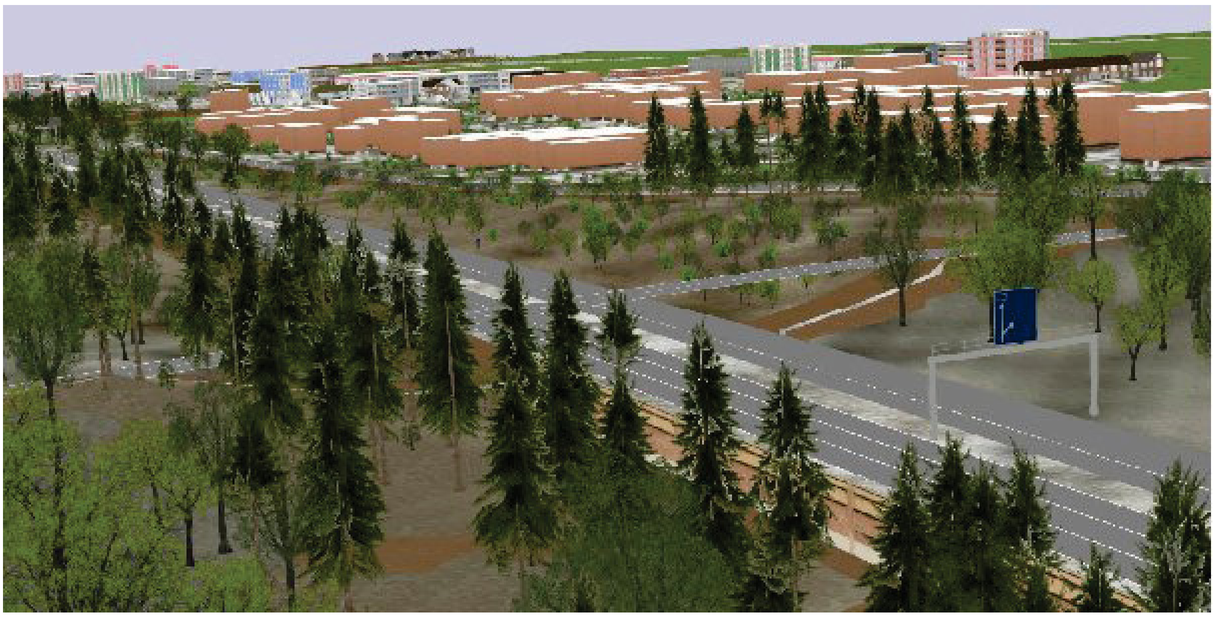

Fig. 5: Sample screenshot of the demonstration area.

The created landscape represents the reality quite successful. Lacks in the level of realism point at lacks in data that is partly incomplete or was not available during test phase. For example not all but necessary information about the roads was available within the first project phase. Also the building creation was basic by taking only the outer edge as 3D design element into account. Nevertheless the first results of SimWorld are very promising so that extending the tool chain towards urban areas is pushed forward. On the one hand the data collection is specialized (as written in the previous paragraphs) and on the other hand the modules for creating the output will be improved such as generating the 3D models of buildings and roads with the help of professional tools to gain more details.

3. Conclusion

The project SimWorld has established a database schema containing many attributes of aspects for creating a driving environment that is more than a city model. Hence it is possible to provide 3D models for driving simulators and also additional data e.g. meta data for communication simulation embedded in the virtual world. Also assistance systems working with optical input can benefit from a realistic appearance of streets and buildings because it is much more close to reality than artificial scenarios. Due to the logical information within the road network it can also be input for traffic simulations (for example for SUMO – Simulation of Urban MObility) or can be support for assistant systems as a local map. With the help of SimWorld these and other applications will have the advantage to work on the same data since the SimWorld database contains more information that only for generating 3D models. Due to the same data basis discrepancies between the applications can be avoided. Also the data basis can be more precise because of the usage of different sources. The project has proven that it is possible to generate vast 3D databases with high precision data. Data reduction is only necessary to tackle visualization performance issues. SimWorld also proves that this kind of data can be processed automatically. This is important to quickly react to changes of the real world for existing databases or generating a complete new area with new data (preferably provided by the same data sources as used before). By using open standards like the scene graph concept and OpenDRIVE it will be easy to make this SimWorld database available for partners (and other applications) to connect to it within projects.

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LEVEL OF DEVELOPMENT AND COST FOR CONSTRUCTING BIM MODEL

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ABSRTACT: *Building information modeling (BIM) has recently attained widespread attention in architectural, engineering and construction (AEC) industries [1, 2, 4, 5]. Several investigations have undertaken to identify or rather quantify the value added by using BIM as well as to test their capabilities and limitations. Leite et al. 2010 [14]evaluates the modeling effort associate with generating BIM at different level of details, ranging from depiction of precise geometry and then to fabrication level precision based on 2 case studies, and further evaluate the impact of LoD in a project in supporting clash detection. It showed more detail in a model can lead to higher precision better supporting decision during design and construction phase. The study also showed from one LoD to another, there was an increase in total modeling time ranging from doubling the effort to eleven folding it. However not much ground has been gained yet in finding practical way to choose the LoD that is needed to develop BIM in a cost effective way. The main objective of this paper is to investigate the modeling effort associated with generating BIM at different levels of details, or termed as Level of Development (LOD), therefore to provide the information needed to choose the LOD.*

KEYWORDS: *Building Information Modeling (BIM), Level of Development (LOD)*

1. Introduction

Building information modeling (BIM) has recently attained widespread attention in architectural, engineering and construction (AEC) industries [1, 2, 4, 5]. Several investigations have undertaken to identify or rather quantify the value added by using BIM as well as to test their capabilities and limitations. One of the key advantages of BIM at the preconstruction phase of a project is identification of conflicts in design prior to construction, saving time during design as well as the accuracy in geometric representation of all parts of a facility, which facilitates the development of detailed information and analysis much earlier in the building process to improve decision making and reduce downstream changes. During construction provide the BIM model a faster and more effective way of communicating platform between interested project parties, support in reducing the amount of rework, improved productivity in phasing and scheduling, faster and more effective construction management with easier information exchange. For the whole lifecycle of a project, these benefits will include in time and cost savings by elimination of unbudgeted change and unplanned change orders, clash detections and elimination of rework. Furthermore, Building Information Modeling (BIM) provides potentially transformational and reusability technology that gives different project participants the opportunity to benefit from the final model product in different fields through its capability to provide a shared visual database of the building components[13]. However, there have not been many research studies investigating the modeling effort associated with generating BIM at different levels of detail (LoD) and the impact of an LoD in a project [14].

Leite et al. 2010 [14]evaluates the modeling effort associate with generating BIM at different level of details, ranging from depiction of precise geometry and then to fabrication level precision based on 2 case studies, and further evaluate the impact of LoD in a project in supporting clash detection. It showed more detail in a model can lead to higher precision better supporting decision during design and construction phase. The study also showed from one LoD to another, there was an increase in total modeling time ranging from doubling the effort to eleven folding it. However not much ground has been gained yet in finding practical way to choose the LoD that is needed to develop BIM in a cost effective way.

The main objective of this paper is to investigate the modeling effort associated with generating BIM at different levels of details, or termed as Level of Development (LOD), therefore to provide the information needed to choose the LOD.

2. Level of Development

The American Institute of Architects (AIA) has been the leading professional membership association for licensed architects, emerging professionals, and allied partners since 1857. The AIA issues a description of the different LOD to evaluate the modeling effort associated with generating BIM at different levels of details. The AIA describes the *Level Of Development* as "the level of completeness to which a component, system or assembly within a Building Information Model is developed". That is to say, the LOD is a term used to express the ability to show different level of details of the components within the BIM model as well as the ability to limit the information required for a specific task. The AIA E202-2008 document defined five progressively LOD. Each LOD builds on the previous level and includes all the characteristics of previous levels.

These are defined as LOD 100, LOD200, LOD 300, LOD 400, and LOD 500 as shown in Table 1. In this paper we focus on specific LODs mainly: LOD100, LOD200 and LOD300.

Table 1: Definition of LOD by AIA E202-2008

LOD	Model Content Requirement	Authorized Uses
LOD 100	Overall building massing indicative of area, height, volume, location, and orientation may be modeled in three dimensions or represented by other data.	Analysis, Cost Estimatingand Schedule.
LOD 200	Model Elements are modeled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Non-geometric information may also be attached to Model Elements.	Analysis, Cost Estimating and Schedule.
LOD 300	Model Elements are modeled as specific assemblies accurate in terms of quantity, size, shape, location, and orientation. Non-geometric information may also be attached to Model Elements.	Construction, Analysis, Cost Estimating and Schedule.
LOD 400	Model Elements are modeled as specific assemblies that are accurate in terms of size, shape, location, quantity, and orientation with complete fabrication, assembly, and detailing information. Non- geometric information may also be at-	Construction, Analysis, Cost Estimating and Schedule.

	tached to Model Elements.	
LOD 500	Model Elements are modeled as constructed assemblies actual and accurate in terms of size, shape, location, quantity, and orientation. Non-geometric information may also be attached to modeled elements.	General Usage.

3. OEM

The Department of Veteran Affairs (VA) issued a practical tool named the BIM Object Element Matrix (OEM) for teams working on real project. The guide comprised two parts: the guide proper, which defines roles and responsibilities, collaboration procedures, approved software, modeling requirements, digital deliverables and documentation standards. The VA BIM object/element matrix manual, series of Microsoft Excel worksheets that defines the level of development of a large number of BIM objects or elements at different stages in the building's lifecycle, which is expansion of the AIA Document E202 NIM protocol Exhibit -2008. It provides standards for information to include in BIM models at creation and at various stages of development. Furthermore, it gives a framework for information to support BIM use on a project. Thus give construction engineers the ability to easily provide the right information, in the right amount at the right time.

The Matrix Spreadsheet as shown in Fig.1 is made up of over a dozen tabbed worksheets. These worksheets are organized and ordered by general Uniformat classification published by the American Construction Specifications Institute, which is a classification system for classifying major components common to most building on the basis of functional elements.

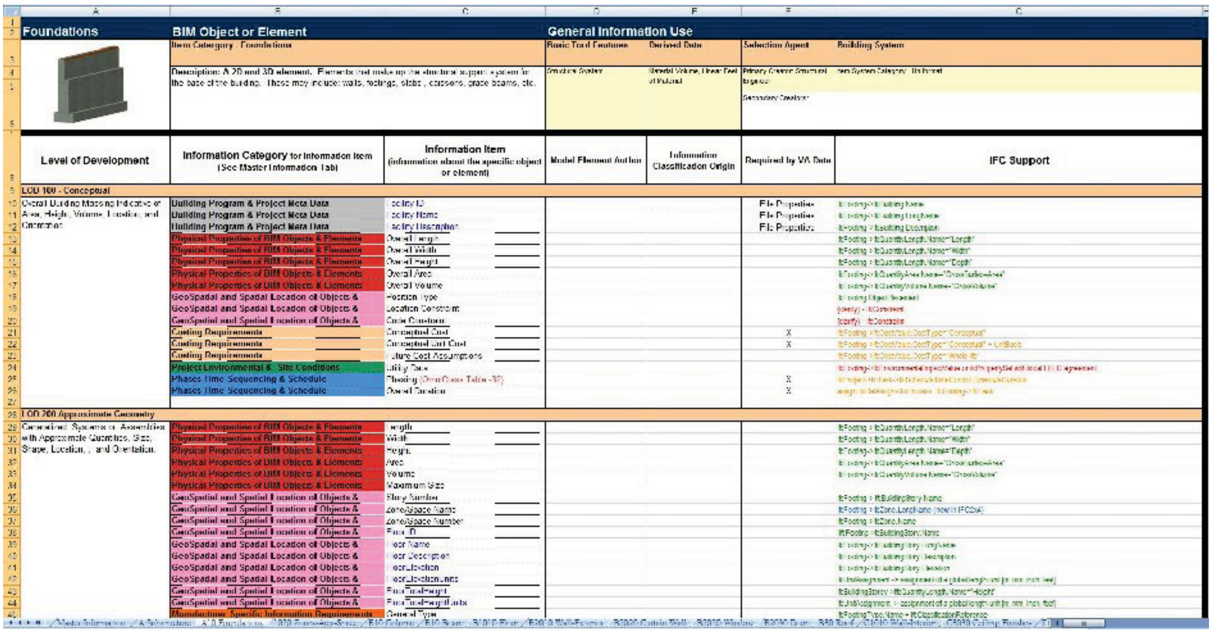


Fig. 1: the BIM Object Element Matrix (OEM)

Uniformat classification is consist of four hierarchical levels: Level 1 includes the 7 main classification: A：Substructure; B: Shell; C: Interior; D: Services; E: Equipment and Furnishing; F: Special Construction and Demo, and G: Building Siteworks. Level 2 subdivides Level 1 elements into Group elements, for instance B Shell includes B10 Superstructure; B20 Exterior Enclosure and B30 Roofing; Level 3 breaks the Group elements further into Individual elements, for instance B20 Exterior Enclosure includes B2010 Exterior walls, B2020 Exterior Windows, and B2030 Interior Doors; level four breaks individual elements into yet smaller sub-elements.

The Object Element Matrix shows the evolution of the architectural spatial model as it is refined during the design process as the project progresses toward construction. As materials and components are selected, generic assemblies shall be assigned material properties, sizes, sustainability credits tracked, and other specific component information defined to clearly identify building features such as walls, floors, roofs, doors, and windows. Excluding the "Read Me First", "Mater Information " and "Info to be inserted" worksheets, there are 28 Worksheets as listed in Table 2.

Table 2: Worksheets of OEM

BIM Object or Element	**Description**
A: Substructure	A 2D and 3D element. An element or category of elements related to the condition of how a building is anchored to a site. These elements are often used in combinations to create structural systems, underground functions, basements, etc.
A10: Foundations	A 2D and 3D element. Elements that make up the structural support system for the base of the building. These may include: walls, footings, slabs , caissons, grade beams, etc.
1020: Zones-Area-Space	A 2D and 3D element. A fill and volume with text/data that is assigned to a bounded space in the model. Can also be used for non-geometric bounding - MEP zones, Departmental &Tool in BIM used to define a bounded or unbounded space and volumn. Tool can be used to define zone types aligned to building systems or organizational data. Ex. Circulation zone, Lighting ZOne, Fire Alarm Zone, Occupancy, Ventalation
B10: Column	A 2D and 3D element. An relatively vertical element most commonly attributed to the structural support system for a building. Columns may be located on the exterior or interior of a building . A column may be a non-structural decorative element only.
B10: Beam	A 2D and 3D element. An relatively horizontal element most commonly attributed to the structural support system for a building. Beams may be located on the exterior or interior of a building . A column may be a non-structural decorative element only.
B1010: Floor	A 2D and 3D element. A horizontal surface element most commonly attributed to the structural support system for a building.
B2010: Wall-Exterior	A 2D and 3D element. A vertical surface element often attributed to the building envelope. An exterior wall shall prevent the intrusion of the elements. An exterior wall may be a structural or non-structural element.
B2020: Curtain Wall	A 2D and 3D element. A vertical surface element often attributed to the building envelope. An curtain wall shall prevent the intrusion of the elements.
B2020: Window	A 2D and 3D element. A vertical surface element often attributed to the

	building envelope. An window shall prevent the intrusion of the elements.
B2030: Door	A 2D and 3D element. A vertical surface element often attributed to the building envelope and egress. An door shall prevent the intrusion of the elements.
B30: Roof	A 2D and 3D element. A horizontal or slanted surface element often attributed to the building envelope. An roof shall prevent the intrusion of the elements and direct water to the appropriate outlet.
C1010: Wall-Interior	A 2D and 3D element. A vertical surface element used to divide rooms within a building. An interior wall shall provide privacy between ajacent spaces. An interior wall may be a structural or non-structural element.
C3030: Ceiling Finishes	A 2D and 3D element. A horizontal surface element used to divide rooms from interstitial spaces located between the ceiling and the building floor or roof system. A ceiling may be individual to a single room or provide plenum space above multiple rooms.
D10: Conveying Systems	A 2D and 3D element. An element attributed to moving people or items from one location within a building to another.
D20: Equipment-Plumbing	A 2D and 3D element. An element attributed to the plumbing system within a building.
D30: Equipment-Mechanical	A 2D and 3D element. An object or element (as in duct work) representing a product used in the mechanical system design.
D30: Air Handling Unit	A 2D and 3D element. An element attributed to the mechanical system within a building. An air handling unit modifies the temperature and may adjust the level of humidity of the air to meet the necessary conditions required by the spaces within the building.
D30: Chiller	A 2D and 3D element. An element attributed to the mechanical system within a building. A chiller modifies the temperature of water or other fluids to be used by air conditioning systems that service the building.
D30: Steam Boiler	A 2D and 3D element. An element attributed to the mechanical system within a building. A steam boiler modifies the temperature of water or other fluids to be used by heating and other systems that service the building.
D30: Water Heater	A 2D and 3D element. An element attributed to the mechanical system within a building. A water heater modifies the temperature of water to be used by occupants of the building.
D40: Fire Protection	A 2D and 3D element. An element attributed to the saftey of occupants of in the event of a fire within a building.
D50: Equipment-Electrical	A 2D and 3D element. An element attributed to the electrical system within a building.
D50: Generator	A 2D and 3D element. An element attributed to the electrical system within a building. A generator provides electrical service in the event of a power failure or disruption of service from the electrical provider.

E10: Object	A 2D and 3D element. An generic element that is placed within a building. An object can be a building element, a furniture item, a piece of equipment, or representation of most anything related to a building. This may include abstract 2D or 3D symbols.
E2010: Fixed Furnishings	A 2D and 3D element. An element that is placed within a building. A fixed furnishing is usually installed as a permanent piece in a building. A fixed furnishing is may be a furniture item, house a piece of equipment, or provide storage within a building.
F1010: Special Structures	A 2D and 3D element. An feature specific element that is part of a building. An special structure can be a building element, a structural design item, an equipment specific construction, or other intergrated item related to a building. These are usually parametric objects available within the authoring tool.
G: Mesh	A 2D and 3D element. An element that provides site context for a building. A mesh describes the three dimensional topography and features of a site.
G10: Site-General	A 2D and 3D element. An element that provides site context for a building.

4. Research Method

In order to evaluate the modeling efforts of LOD, this research adopts the definition of LOD by AIA E202-2008, and applies OEM to generate each BIM element at LOD 100, LOD 200, and LOD 300 with Revit Architecture by a researcher who has undertaken 18 hour training course of Revit Architecture and is fluent with the modeling environment. The research kept track of the time needed for each element. As Fan et al.2010 showed each modified or customized element takes on average two hours of labor time when compared with the two minutes for each built-in element, and the efforts needed for each customized element might vary as the amount of customizing differs. Therefore this research evaluates only the built-in elements of Revit, which covers the classification A Substructure to C Interiors of CSI master Format.

Followed by it, this research took a typical research building of National Taiwan University as example, generated BIM at LOD 100, LOD 200 and LOD 300 for this building, and recorded the number of elements and time needed.

Summarizing the above mentioned research efforts, this research proposed an algorithm to estimate the approximate time needed to generate BIM at LOD 100, LOD 200 and LOD 300 with Revit Architecture built in elements.

5. Case Project

The case project focuses on a typical research building of National Taiwan University. It is a precast concrete construction RC building possessing a seismic isolation system at the mid-story. This building consists of an underground parking basement and nine floors with a total height of approximately 41.4 m and a total floor area of 9686.44 m². The construction period was 6 months. Fig. 1 shows the project visualization and a photo taken on-site[10, 13].

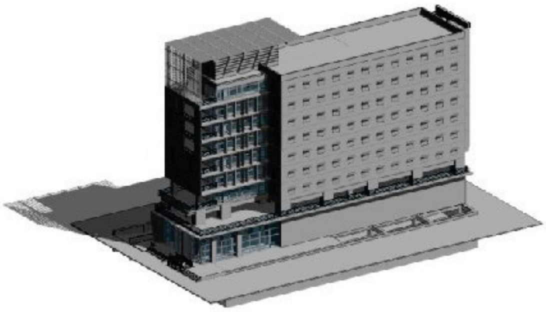
 

Fig. 2:. Project visualization at LOD300 (left) and a photo taken on-site (right)

6. Results

This research showed the time to model a single element with a built-in element around 1 minute which is the same regardless of its LOD, however for each LOD the information needed to be filled in for each element at different LOD differs. Table 3 shows the time to fill in information item at different LOD 100 to LOD 300 for each element from Category A to C.

Table 3: Time to fill in information for each element

	LOD100	LOD200	LOD300
A10 Foundations	3	3.75	8.75
B10 Column	3.5	4.75	15
B10 Beam	3.25	4.5	17.25
B1010 Floor	3.25	4.75	15.25
B2010 Wall-Exterior	3.5	4.5	16
B2020 Curtain Wall	3.5	5	21.75
B2020 Window	3.5	5	21.75
B2030 Door	3.5	5	22.5
B30 Roof	3.5	4.75	15.5
C1010 Wall-Interior	3.5	4.5	14.5
C3030 Ceiling Finishes	3.25	4.5	13.5

Table 4, Table 5 and Table 6 showed the number of element to generate the case project at LOD 100, LOD200 and LOD300. It also showed the time in minutes needed for generate each element. As in the case project, the layout of Floor 3 to Floor 9 is identical, therefore the time to generate the elements of an identical floor following the first one is decreased to 1 minute as the elements of such floors could be copied from the first one.

Table 4: Number of Element and Time Needed for BIM at LOD100, LOD200 and LOD300

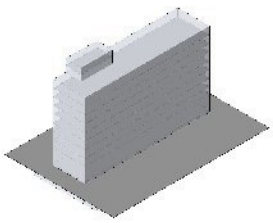
LOD	BIM	Type of Element	Number of Element (N)	Te	Ti	Total (Min.)
LOD100		A10 Foundations	1	1	3	196
		B10 Column	0	0	3.5	
		B10 Beam	0	0	3.25	
		B1010 Floor	12	1	3.25	
		B2010 Wall-Exterior	0	0	3.5	
		B2020 Curtain Wall	0	0	3.5	
		B2020 Window	0	0	3.5	
		B2030 Door	0	0	3.5	
		B30 Roof	1	1	3.5	
		C1010 Wall-Interior	0	0	3.5	
		C3030 Ceiling Finishes	0	0	3.25	

Table 5: Number of Element and Time Needed for BIM at LOD200

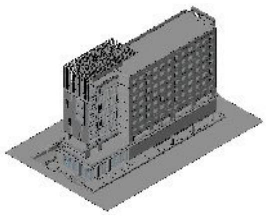
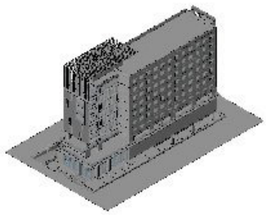
LOD	BIM	Type of Element	Number of Element (N)					Te	Ti	T
			Foundation	1F	2F	3F	RF			
Repetition						7				
LOD200		A10 Foundations	84	0	0	0	0	1	3.75	399
		B10 Column	35	55	27	20	18	1	4.75	898.25
		B10 Beam	54	77	62	60	0	1	4.5	1398.5
		B1010 Floor	4	4	1	1	2	1.5	4.75	82
		B2010 Wall-Exterior	0	0	6	0	48	0.5	4.5	270
		B2020 Curtain Wall	0	423	0	154	4	1	5	3493
		B2020 Window	0	0	0	50	0	0.35	5	274.5
		B2030 Door	0	4	0	8	0	0.35	5	71.2
		B30 Roof	0	0	0	1	1	1.5	4.75	19.5
		C1010 Wall-Interior	84	94	0	71	0	0.5	4.5	1252
		C3030 Ceiling Finishes	0	0	0	0	0	1	4.5	0

Table 6: Number of Element and Time Needed for BIM at LOD300

LOD	BIM	Type of Element	Number of Element (N)					Te	Ti	T
			Foundation	1F	2F	3F	RF			
Repetition						7				
LOD300		A10 Foundations	84	0	0	0	0	1	8.75	819
		B10 Column	35	55	27	20	18	1	15	2487
		B10 Beam	54	77	62	60	0	1	17.25	4624.25
		B1010 Floor	4	4	1	1	2	1.5	15.25	208
		B2010 Wall-Exterior	0	0	6	0	48	0.5	16	891
		B2020 Curtain Wall	0	423	0	154	4	1	21.75	13224.75
		B2020 Window	0	0	0	50	0	0.35	21.75	1112
		B2030 Door	0	4	0	8	0	0.35	22.5	281.2
		B30 Roof	0	0	0	1	1	1.5	15.5	41
		C1010 Wall-Interior	84	94	0	71	0	0.5	14.5	3742
		C3030 Ceiling Finishes	0	0	0	0	0	1	13.5	0

Summarizing the above mentioned research efforts, it is concluded that :

1. To develop a BIM at LOD100 with Revit Built-in elements, the time needed is

   $$T_1 = \sum N_i * (T_i + T_e)$$

   T_i: Time to fill in Information, as shown in Table 3.

   T_e: Time to Generate a built-in Element，equals 1 minute according to this study.

   N_i: the number of element for the ith Type of Element

2. To develop a BIM at LOD200 with Revit Built-in elements, the time needed is

   $$T_2 \text{ and } T_3 = \sum_R \sum_N N_i(T_i + T_e) + (R-1)$$

   T_i: Time of Information Item

   T_e: Time to Generate a built-in Element ，equals 1 minute according to this study.

   R : Repetition of the Floors

3. The formula to calculate the time needed to develop a BIM at LOD 300 with Revit Built-in elements is identical to the one to develop a BIM at LOD200, except the Ti adopt is of different values.

7. Conclusion

While potential benefits of Building information modeling (BIM) has been much talked about, there have not been many research studies investigates the modeling efforts associated with generating BIM at different LOD.

In order to evaluate the modeling efforts of LOD, this research adopts the definition of LOD by AIA E202-2008, and applies OEM to generate each BIM element at LOD 100, LOD 200, and LOD 300 with Revit Architecture by a researcher who has undertaken 18 hour training course of Revit Architecture and is fluent with the modeling environment. The research kept track of the time needed for each element. As Fan et al.2010 showed each modified or customized element takes on average two hours of labor time when compared with the two minutes for each built-in element, and the efforts needed for each customized element might vary as the amount of customizing differs. Therefore this research evaluates only the built-in elements of Revit, which covers the classification A Substructure to C Interiors of CSI master Format.

Followed by it, this research took a typical research building of National Taiwan University as example, generated BIM at LOD 100, LOD 200 and LOD 300 for this building, and recorded the number of elements and time needed.

This research summarized from keeping track of the time needed to generate each element meeting the requirement of OEM at LOD 100, LOD 200, and LOD 300 with Revit Architecture and time needed to to generate BIM at LOD 100, LOD 200 and LOD 300 for a typical research building, this research proposed an algorithm to estimate the approximate time needed to generate BIM at LOD 100, LOD 200 and LOD 300 with Revit Architecture built in elements, thus to provide the information needed to choose the LOD.

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STUDY ON BUILDING INFORMATION NEEDED UNDER A DISASTER IN THE BUILDING INFORMATION MODEL ENVIRONMENT

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ABSTRACT: *Building information model (BIM) is one of the important techniques that can help various stakeholders of a building project finish their work efficiently and effectively. BIM uses the 3D model to represent every object in the design and construction phases, including shapes, structural behaviors, cost and material properties of building components. Because BIM can be regarded as a single database for all information needed during the design and construction phases of a building project, it may be able to be applied to the disaster mitigation and response domain. When a disaster hit a building, firefighters usually do not have much time to respond. They need to make decisions very quickly, based on current information they can obtain. Since BIM contain comprehensive design and construction information regarding the building, how to retrieve such information and immediately transform it into the format easily understood by firefighters would be very helpful. Hence, there is a need to investigate how BIM can help disaster mitigation officials make a decision and respond appropriately. This research will begin with extensive interviews with experts from the disaster mitigation and response domain. The information requirements regarding BIM relevant to disaster mitigation and response will be firstly identified. Then, the BIM Information Retrieval Function (BIRF) system will be designed in order to provide disaster mitigation officials with adequate information from BIM. The Spatiotemporal Facility Vulnerability Assessment (SFVA) system will be designed as well in order to further BIM for disaster mitigation purposes. Several test cases will be collected and verified for the proposed system. Conclusions will be draw and recommendations for future research will be discussed.*

KEYWORDS: *Information integration, fire responses, building information model, facility vulnerability assessment.*

1. Introduction

Disasters could potentially affect a building and then bring to the loss of possession. Therefore, it is importance to mitigate disasters so as to preserve human lives and assets inside the building. When a disaster occurs, fire, police and emergency medical responders might need an integrative information system that can render detailed geometry and material-related information of the building on demand, in order for them to quickly assess the current situation, find evacuees, deploy resources, and notify the control center of decisions made as the event progresses. There are some building automation systems that manage dynamic information such as power, gas, water systems and so on. Such systems generate potential data that can be used for emergency responses but are currently distributed and disintegrated. In addition, a great number of data might cause confusion because emergency responding is necessary to react in a short time and needs a simple way to display information (Jones et al., 2005). Due to the increasing use of the Building Information Model (BIM) technology, it may be a good candidate source of providing first responders with such emergency information. Accordingly, BIM is chosen as a methodology integrating with different kinds of information and presents information in a simple way.

BIM not only brings diverse stages of a building's life cycle data together but also includes abundant properties from divergent views. Though BIM attempts to share and exchange information, most applications of BIM concern with the construction process rather than the post-construction issues such as disaster mitigation, which makes more use of attributes and endows meaning with data. It might be meaningless if such plentiful information from BIM was not analyzed and used in a proper way. Currently there are few researchers employing BIM for disaster mitigation. National Institute of Standards and Technology (NIST) illustrated an example scenario of their system, Incident Command Tactical System (ICTS) (Jones et al., 2005) – not a BIM-based one but integrating information and displaying in 3D way – which can be considered as a prototype similar to BIM applications. Besides that, Spearpoint (2007) dealt with the data-exchanged problem that lacks the standardization between different software tools. Spearpoint tried to transfer an IFC building product model to a fire simulation program, but this research can hardly be considered as utilization of BIM information. Other researcher combines with the Geographic Information System (GIS) technique to support the fire response management process (Isikdag, 2008). However, it focuses more on the geospatial environment, and BIM is merely used as a data warehouse here. Another researcher proposed a method using BIM to improve the indoor positioning of Computer Aided Facility Management (CAFM) systems, in which BIM is also not mainly concerned (Bernoulli, 2008).

Hence, in this research, we proposed a spatiotemporal database-based approach that can transform relevant data from BIM to the information needed by first responders. Section 2 discusses the overview of the disaster mitigation process so as to understand the need to collection static and dynamic information of a building after it is built. Section 3 introduces the spatiotemporal database technique that is utilized to provide first responders with relevant, integrative information from BIM and other sources. Section 4 discusses the proposed software architecture with a BIM example. Section 5 presents research conclusions and recommendations.

2. Disaster Mitigation Process

The disaster management process consists of six disaster-related phases: (1) identification; (2) prediction; (3) mitigation; (4) preparation; (5) response; and (6) recovery. The identification phase involves ascertaining any opportunity pertaining to assets, i.e., people, fire sprinklers, hospital beds, etc., that may be affected by a disaster. The prediction phase consists of scientific analysis tasks, including meteorological, geologic, hydrologic, agricultural, environmental, epidemiologic calculations and simulations. The mitigation phase concerns active reductions of a disaster's impact, whereas the preparation phase includes needed actions to contend with the portion of a disaster's impact that cannot be mitigated. The response phase focuses on real-time actions as a disaster evolves, whereas the recovery phase deals with how to restore community assets affected by a disaster. Current researchers focus more on the last two phases because they require integrative system thinking and have the potential to significantly lessen the impact.

Researchers have analyzed requirements of a disaster mitigation system (DMS) covering all six phases of the disaster management process. Briefly, a DMS is designed to significantly lessen the loss of human lives and the economic costs of a disaster, and should have three components: (1) a baseline database: which contains the basic information of the assets affected by a disaster; (2) spatial querying: which can provide disaster management officials with a graphical interface showing designated geographical information of the disaster and assets, e.g., locating the shortest evacuation path and optimizing the resource distribution; and (3) ubiquitous computing: which means redundant computing resources should be allocated to execute the DMS simultaneously.

However, the rescue operations after September 11, 2001 were recognized as lack of an integrated data repository that can be used to predict possible subsequent building failures. Disaster management officials or decision makers need to know not only direct impact on assets of a disaster but indirect impact on the other aspects of a building. Since a building involves not only structural components but other electrical apparatus that generate dynamic information, the only way to collect such data is for the building owner to ask equipment supplier to upload data as a part of the building commissioning process. Some equipment suppliers build very detailed computerized models describing their own facilities, but this kind of information may involve a company's confidential data and cannot be completely shared with the others. Security concerns must be addressed in advance of data collection from different equipment suppliers. A formal model that can describe predict a disaster's impact on a building is highly desired.

3. Temporal Data Processing

Each event during and after a disaster may be associated with a different time scale. For example, if an accident destroys a power switch facility, the failure due to switching over voltages may ruin other power facilities within milliseconds. Shortage of fuel support as a result of blockage may take months to fix the problem but might not affect the power generation process immediately. The need of the multi-scale time hierarchy associated with BIM and emergency responding was reported as one of the most difficult research challenges in this area.

One advanced database technique that has emerged as a main focus of many spatiotemporal information systems such as the digital battlefield in the military is to keep track of object locations over time and to support temporal queries about future locations of the objects. Called a moving objects database (MOD) or spatiotemporal objects database (SOD), this technique is based on the theory of temporal databases. MOD aims to deal with geometries changing over time and to simplify the data update process through the use of dynamic attributes, and thereby has the potential to eliminate or reduce some of the associated challenges and complications. The method employed by MOD to process the time dimension for each moving object may serve as a starting point for activity modeling.

In MOD, there are two time dimensions associated with each time-sensitive attribute: valid time and transaction time. The valid time refers to the time in the real world when an event occurs or a fact is valid. The transaction time refers to the time when a change is recorded in the database. Formal definitions for Dv (valid time) and Dt (transaction time) are listed as follows:

$$Dv = \{to, \ldots, ti, \ldots, ½\} \quad (1)$$

$$Dt = \{to, \ldots, tj, \ldots, now\} - \{now\} \quad (2)$$

In Eq. (1), to represents the very beginning of the universe, and a specific time point is referred to as ti. ½ represents the eternity of the universe. Hence, Dv is a set of time points, ranging from to to ½. In other words, the valid time dimension can represent the entire time domain. In Eq. (2), tj represents a past time point. The current time is represented as now. The value of now advances as the clock ticks. Any time point beyond now is future time. Hence, Dt is a set of time points, ranging from to to the time point before now.

In practice, two attributes (begin_date and end_date) should be added for the valid time dimension, and three special values should be defined to denote the concepts of the very beginning of the universe, “forever”, and “now” respectively in the database. The transaction time dimension can represent any time before “now”, and only one attribute (tran_date) should be added for it. For example, the duration of a maintenance activity (Activity-1) is defined by a manager as being January 1, 2009 to March 1, 2009, which is in the Dv domain. The manager enters this activity information, including the geometric boundary and the schedule, into a computer on November 1, 2008, which is in the Dt domain, but the schedule is changed on January 5, 2009. The new schedule runs from February 1, 2009 to April 1, 2009. There is another maintenance activity (Activity-2) scheduled to be performed from March 1, 2009 to May 1, 2009. The manager enters the second maintenance activity into the computer on December 1, 2008 (see Fig. 1). Indeed, the three database records regarding the two activities must be persisted individually since each data entry may be associated with a permit application and fees. For instance, a building owner may ask the equipment supplier of the first activity to pay additional fees for the time period between January 1, 2009 and January 5, 2009, although no one in fact performs any work at that time. Recording the two time dimensions of each activity helps project stakeholders to retrieve not only the latest date but also historical ones for future auditing purposes.

Further, the duration of a maintenance activity may be associated with a different time scale. For example, if an accident destroys a power switch facility, the problem due to switching over voltages needs to be fixed within a few hours. However, it may take months to fix the problem of leaks of water lines. The need for a multi-scale time hierarchy associated with each maintenance activity is evident; however, current GIS techniques cannot provide an appropriate solution to satisfy this need.

As advocated by Zimanyi, because the temporal extensions of SQL have not reached acceptance in the standardization committees, manipulating time-varying information should still rely on the use of standard SQL. Hence, in order to perform the temporal query jobs, the research team followed this suggestion to develop several temporal functions that use standard SQL only. However, because the spatial extensions of SQL now have the standard specifications, namely SQL/MM, the research team employed these standard-based functions to perform the spatial query jobs. SQL/MM has been incorporated into the ISO/IEC 13249 specification and is the effort to standardize extensions for multi-media and application-specific packages in SQL. Part 3 of SQL/MM is the international standard that defines how to store, retrieve and process spatial data using SQL and was originally derived from OGC.

4. Proposed Architecture

The proposed architecture to extract information from BIM for first responders is shown in Figure 1. Currently BIM programs can export files in the IFC format. Our basic strategy is to transform all data in the XML format so that the XSLT technique can be seamlessly utilized to converse these data into an integrative information base. So, the IFC file should be transformed to an IFC-XML file by using an IFC2XML tool. Moreover, since an IFC-XML file is usually too large to process, an XML database is used in this research to overcome this problem. In a XML database, XML documents can be very large and their query performance can be reasonably maintained. Once all information from the BIM sources is transformed into the corresponding XML documents and stored in the XML database, integration of static and dynamic information of a building can be commenced. It should be noted that dynamic information sources of a building means these apparatus that can generation time-related data such as monitoring of electrical usage. Then, the XSLT technique is used to converse all XML documents into the spatiotemporal database implemented in the PostGIS environment.

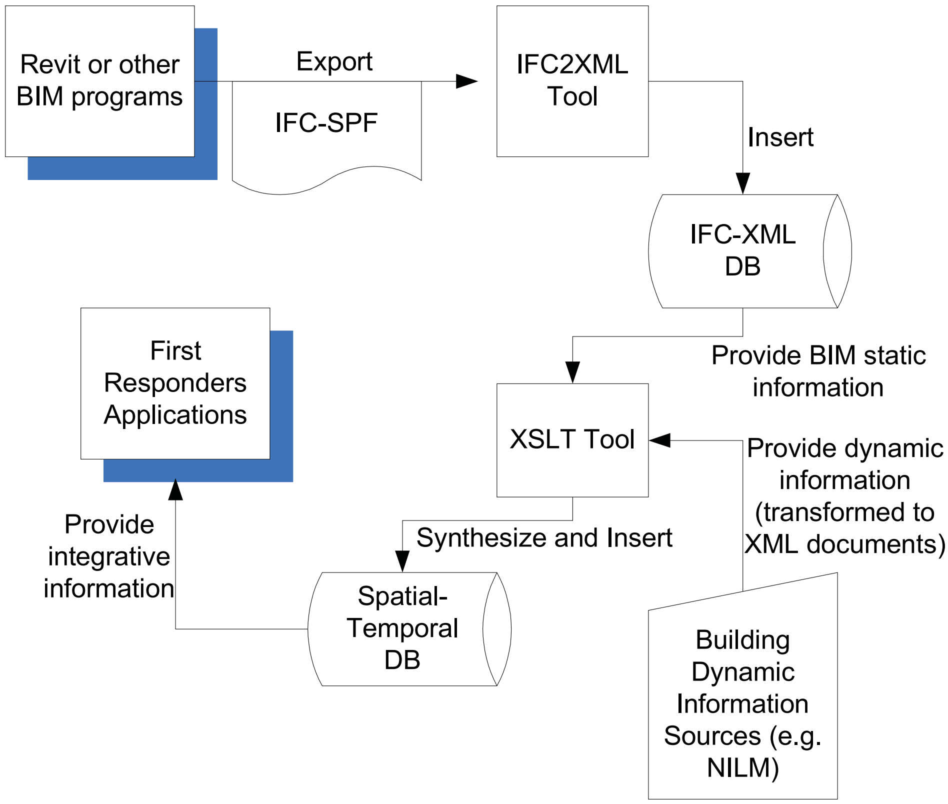

Fig. 1: Software architecture for integrating static BIM information and dynamic equipment information of a building.

Several conformation rules were designed to ensure data consistency during model transformation. This research locates the problem of disaster mitigation only in supporting fire responding strategies and illustrates a methodology using BIM. First, necessary information categories that can be provided by BIM for first response are investigated by interviewing emergency responders. BIM is considered including 3D spatial and material information that may be beneficial in decision process. After necessary information categories from BIM are defined, BIM Information Retrieval Function (BIRF) is designed for retrieving needed information from BIM. Retrieved information is going to be transferred to the format of Fire Dynamics Simulator (FDS) to simulate the condition when a building is on fire. Results from FDS are going to be imported to the BIM for validation. Maintenance records from BIM are also retrieved not only to analyze the condition during emergency but to predict the trends in the future. Ontology techniques are utilized as well to assist in reasoning subsequent events.

The research intends to utilize latest spatiotemporal database technologies to enhance the capability of BIM as well as integrates the ontology reasoning mechanism to accelerate emergency response process. Finally, the methodology is expected to become a sample pattern of solving the problems of integrating information from different views.

The Taipei Railway Main Station is used in this research to demonstrate the proposed system. Figure 2 shows the 2D view of the station. The BIM model is shown in Figure 3.

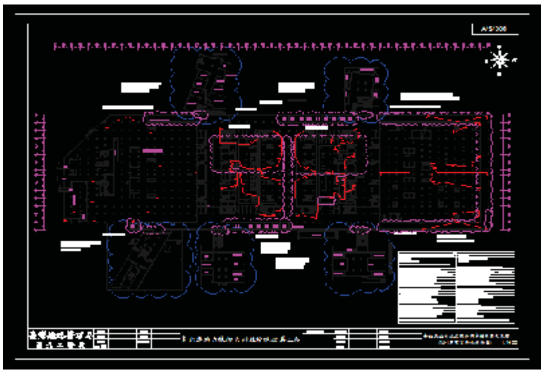

Fig. 2: Traditional CAD model of the Taipei Railway Main Station.

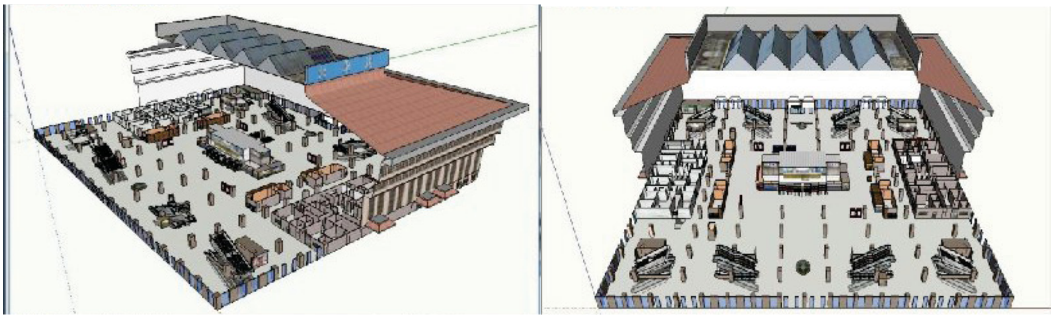

Fig. 3: The BIM model of the Taipei Railway Main Station.

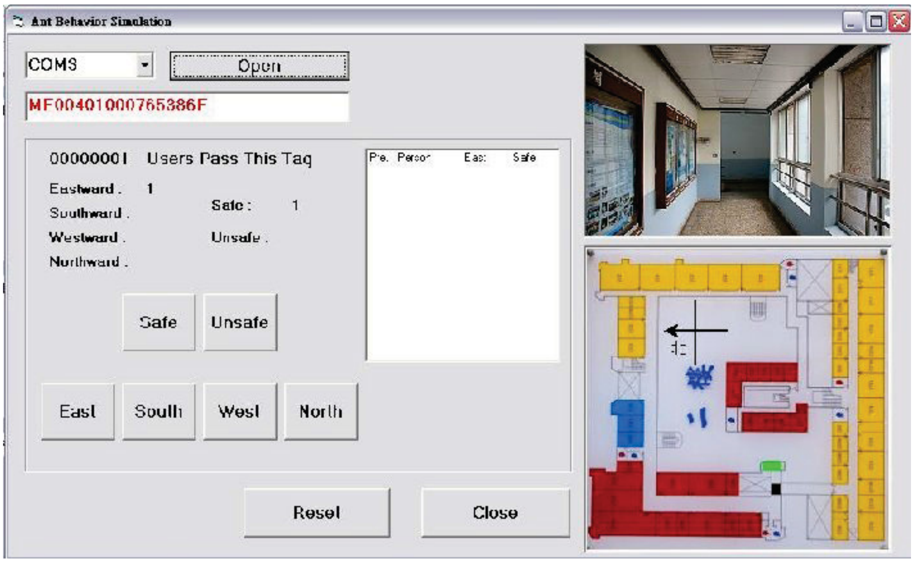

Fig. 4: First Responder's View of the Synthesized Information.

Figure 4 show the synthesized view of the BIM and dynamic equipment information. A first responder can navigate the building by clicking the East / South / West / North buttons. The BIM information will be shown in the right-bottom box of the form. Currently only the plan view is displayed. The right-top box of the form shows the real pictures of the building. The first responder can browse for any potential safe or unsafe objects in the listbox of the form.

5. Conclusions

This research has proposed a software architecture to integrate the static (BIM) information with the dynamic, equipment-related data. The spatiotemporal database and XSLT techniques were utilized to store and synthesize the data. The BIM information is used to show the geometry aspect of the building. Materials-related information that can be extracted from BIM is used to indicate whether or not they will become safe or unsafe when a fire event occurs. First responder may be able to use this tool to see what may happen inside a building before physically entering it. Further enhancement of the system is needed in order to integrate more dynamic information from different equipment suppliers and/or other BIM programs.

6. Acknowledgements

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INTEGRATING INTERACTIVE 4DCAD WITH WIDE-AREA AUGMENTED REALITY FOR ON-SITE CONSTRUCTION PLANNING

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ABSTRACT: *It is widely acknowledged that robust and effective construction planning is one of the most important tasks undertaken in a construction project. However much research has revealed the considerable amount of mental processing associated with traditional planning practices. While the absence of a spatial context within scheduling documentation, or temporal information within a 3D model, means project participants must mentally link the task information with building elements to create their own personal 'mental 4D model'.*

4D CAD unambiguously visualizes the intent of a construction schedule, removes the mental abstraction associated with conventional planning practices and improves communication throughout the planning team by enabling both technical and non-technical stakeholders to fully comprehend the project schedule. Some research efforts have sought to advance the inherent communicative and collaborative abilities of 4D CAD through integration with real time visualization techniques.

Augmented reality (AR) is a visualization technique that enhances the view of the real environment by overlaying virtual objects registered in the real worlds coordinate frame. Limited initial investigations into AR for construction planning have mainly seen developments for in-place product and process visualization or post scheduling review.

A new approach to 4D CAD is thus proposed, to provide accurate mobile real time 4D for interactive site-based scheduling (AR4D). The system utilizes an IFC based model file into a purpose written 4D engine implemented within a commercial VR authoring tool. RTK-GPS tracks positioning, an electronic tilt-compensated compass provides orientation and the live video is merged with the simulation through a HMD. Initial prototypes have revealed its feasibility, while further work will implement the tool on a live construction project.

KEYWORDS: *Augmented Reality, RTK GPS, Interactive 4D CAD, BIM, IFC, Collaborative Planning*

1. Introduction

It is widely acknowledged that effective construction planning is one of the most important tasks in a construction project and is a crucial requirement for its successful completion (Waly and Thabet 2003, Staub-French and Khanzode 2007). Effective communication and coordination starting from the development of the construction schedule right through to its implementation is itself a critical factor of successful project planning (Allen and Smallwood 2008). However the inherently fragmented nature of the construction industry, its reliance upon a predominantly document-centric workflow and problems related to software interoperability inhibit communication between project stakeholders, which in turn impacts negatively on coordination efforts (Isikdag and Underwood 2010). Isikdag and Underwood (2010) explain that a system of collaborative working should provide the ability for inter-participant communication whilst allowing each participant to perform their own work in their own way; furthermore they postulate that effective collaboration on construction projects is directly related to the level of effective information coordination and communication between all project stakeholders.

A great deal of information regarding work activities and the complex relationships that exist between them is conveyed through a construction schedule. Nevertheless, it is widely acknowledged that the considerable amount of mental information processing associated with traditional planning practices can easily overburden the planning team, leave the schedule open to multiple interpretations and thus cause problems with effective communication and coordination between the project members (McKinney and Fischer 1998, Waly and Thabet 2003, Feng *et al*. 2010).

The conventional methods of schedule communication such as Gantt charts, bar charts and network diagrams are still prevalent within the construction industry (Benjaoran and Bhokha 2009). However, while adequate for describing the *who* and the *when* of the construction task, these traditional schedule communication techniques lack the context of the *where* (Koo and Fischer 2000). Conversely, the increasingly prevalent 3D architectural model effectively and intuitively describes a building's spatial relationships, but lacks the ability to convey the temporal nature of a construction project (Doulis *et al*. 2007). This absence of temporal information within the 3D model, or a spatial context within the scheduling documentation, leaves project planners needing to mentally link the scheduled task information with the corresponding physical elements of the proposed building to create a *mental 4D model* (McKinney and Fischer 1998).

2. 4D CAD

Since the early 1990s, research efforts have shown the potential benefits and insights that 4D CAD techniques can bring to planning process (Koo and Fischer 2000, Staub-French and Khanzode 2007). 4D CAD removes the abstraction associated with conventional planning approaches by explicitly linking schedule tasks with a CAD model and thus links a project's spatial context with the temporal information to provide a graphical simulation of the construction process over time (McKinney and Fischer 1998, Staub-French and Khanzode 2007). To view this another way, 4D CAD simulations can be understood as a visualized link between the 3D elements in a CAD model, the Product Breakdown Structure (PBS), and the construction activities within the schedule, the Work Breakdown Structure (WBS) (Zhou *et al*. 2009).

By mapping task information to the corresponding elements in a 3D model, 4D CAD can provide clear visualization of the schedule intent and thus enable both technical and non-technical stakeholders to fully comprehend the information conveyed within the construction documentation (Dawood and Sikka 2008, Golparvar-Fard *et al*. 2009). Dawwod and Sikka (2008) illuminate on how democratization of the schedule information enables all participants to appreciate the spatial, temporal or sequential relationships and constraints of a project, whilst facilitating inter-team communication. A further experimental study indicates how 4D visualizations facilitate the resolution of sequencing problems in advance, whilst enabling the planning team to detect more logical errors, more accurately and in less time than a comparable team using 2D graphics (Kang *et al*. 2007).

Conventionally a 4D simulation is created by manually linking tasks within a CPM schedule with their corresponding 3D elements using specialist third party software (Collier and Fischer 1996). This manual linking approach is commonly found in commercial 4D solutions, however, by requiring the input of both a model and a completed schedule, Waly and Thabet (2003) argue that this type of 4D CAD application should not be seen as a planning tool, but more as a tool for post planning review. Zhou *et al.* (2009) concur with this view and further postulate that interactive distributed virtual environments facilitate a more open-ended approach to construction scheduling than conventional practices by providing a unified workspace with a shared social context.

2.1 Applications of 4D CAD

The considerable volume of research relating to 4D CAD is cited by some as evidence of its potential for usefulness on construction projects (Staub-French and Khanzode 2007). Koo and Fischer (2000) demonstrated how 4D modeling not only allows the workability of a schedule to be evaluated but also promotes interaction and collaboration between project members, while others have illustrated how it assisted with creating, analyzing and communicating the schedule (Haymaker and Fischer 2001). One study demonstrated how a collaborative web-based 4D visualization allowed geographically dispersed personnel to work more effectively (Kang *et al.* 2007), while Staub-French and Khanzode (2007) further reveal that 3D and 4D modeling increase productivity, reduce rework and lead to a reduction in overall project duration.

Waly and Thabet developed a Virtual Construction Environment (VCE) in which the construction sequence is captured from the order in which components in the product model are manipulated by the user. This manual 'drag and drop' scheduling mechanism utilizes the planners knowledge and experience, and augments it with a knowledgebase of available means, methods and resources (Waly and Thabet 2003). 4D-CAD-Safety is a planning review tool that seeks to integrate safety planning with construction simulation. Using AutoCAD for visualization, MS Project for schedule creation and a database to store all product, process and safety information, a significant feature of this approach is how it attempts to support the work of the safety planner through the provision of a context-driven safety library (Chantawit *et al.* 2005). While others have proposed the integration of construction task and site layout planning within a 4D simulation environment (Ma *et al.* 2005).

Heesom (2004) developed a 4D space planning application with a mechanism for reorganizing the granularity of the model elements through decomposition or grouping, while the use of Unified Classification (Uniclass) product codes in the CAD model enabled automated linking of PBS and WBS. Ma et al. (2007) advocate *a priori* grouping of 3D CAD objects by WBS code to enable automatic task-object linking. A proposed *n*D modeling tool further extends the dimensionality of the construction simulation model with the support for decision-assistive information such as cost, sustainability, energy requirements and even life-cycle maintenance (Lee *et al.* 2005). Model-based scheduling has been proposed that brings together architectural design, construction scheduling, cost management and quantity take off based around a Building Information Model and it's data model file, IFC (Industry Foundation Class) (Weise *et al.* 2009). A later example proposes a Building Information Model (BIM) based virtual 5D planning and construction simulation environment, where cost is the fifth dimension (Popov *et al.* 2010).

2.1.1 Collaborative 4D Planning

The increasingly global nature of the construction industry has already created a need for personnel in different geographical locations to work collaboratively (Faraj *et al.* 2000). Moreover it has been shown that the effectiveness of collaboration and communication efforts within a project is improved through proper coordination (Ellis *et al.* 1991). Some research efforts suggest that effective collaboration can only occur through effective coordination and communication of the project information (Isikdag and Underwood 2010), while others elucidate that true collaborative planning is a result of combining collaborative and communicative work practices with 4D CAD principles (Heesom and Mahdjoubi 2004).

It is evident from the research that conventional 4D CAD already has the potential to promote collaborative working practices (Koo and Fischer 2000, Haymaker and Fischer 2001, Dawood and Sikka 2008). Experimental evidence has shown how web-based chat and browser-based visualization of the construction sequence enabled team members at different locations to quickly and accurately find more logical errors, with less communication time than when using 2D representation of the design (Kang *et al*. 2007). Zhou et al. (2009) explain that prevailing 4D CAD applications are for planning review rather than for schedule creation, however by providing real time interaction with a unified 3D model, they suggest that distributed collaborative 4D CAD provides geographically dispersed planning teams with a shared social context in which they can leverage individual and social creativity towards the generation of a robust construction schedule.

2.1.2 Virtual Planning Environments

Virtual Reality (VR) has long been utilized in construction research to enhance information communication and improve pre-construction evaluation of the design and schedule (Sriprasert and Dawood 2003). VR allows users to navigate around a Virtual Environment (VE), in 3D, and interact in real time with large and complex visual data sets (Woksepp 2007). This ability to represent complex spatial information intuitively makes this technology very well suited for enabling a shared and robust understanding of a proposed construction schedule (Woksepp *et al*. 2005). Furthermore Doulis et al. (2007) suggest that the ability of immersive VR technology to convey the spatial characteristics and relationships of a project intuitively and at a realistic and natural scale has almost predetermined its use for visualizing the construction process.

Some research has demonstrated the ability of VR to provide communication-enhanced, real time, real scale visualization of the construction within an interactive virtual environment, however the emerging field of Augmented Reality offers the possibility of intuitive contextual visualization and interaction with a 4D construction model. Immersion within a full-scale VE has been shown to assist with visual comprehension and communication of the construction schedule; however it is here proposed that removing the real world context from the user's field of view abstracts the context of a project and also precludes the safe use of VR for outside working. Related to VR technologically, Augmented Reality (AR) is a computer-based visualization technique that has more recently come to the fore in construction planning research. But while VR deducts reality by completely immersing the user, AR enhances a user's perspective on the world by augmenting the real view with virtual objects registered in the users 3D coordinate frame, so they appear to co-exist (Azuma 1997).

3. Augmented Reality

Augmented reality (AR) is an advanced visualization and communication technology that combines digitally stored and spatially referenced visual, aural or even haptic information with the physically real environment in real time (Azuma 1997). AR technology facilitates straightforward collaboration, intuitive interaction and integration of digital information to provide augmented workspaces which retain the familiar context of the physical world (Schnabel *et al*. 2007).

Fig. 1: Milgrams' continua for defining Mixed Realities

AR is a subset of VR, which itself is a subset of Mixed Reality (MR) an all-encompassing definition of augmented spaces set out in a seminal taxonomy of computer display conditions in which real and virtual worlds are combined. Utilizing a scale ranging from reality at one extremity and virtual at the other, Milgram and Kishino (1994) classify the various subsets of MR by way of their position along the Reality-Virtuality (RV) continuum. This RV continuum is further supported by the parallel Extent of World Knowledge (EWK) continuum which classifies systems according to the extent of the knowledge held by the system about the world view being presented to the user. To clarify, a VE is described as a completely modeled environment, whereas in a real environment the only thing the computer may be aware of is the video file or input stream being displayed. Residing between reality and the middle of RV continuum (see Fig.1), AR will possess imperfect or uncertain information regarding the contents of the Mixed Environment (ME). For instance the geometry and positioning information of a 3D model may be known, but the system will typically have no information regarding the real environment into which these virtual augmentations will be merged and can thus be described as possessing a partially modeled world view.

Azuma (1997) defines properties common that all AR systems should possess:

1. Blending the real and the virtual within a real environment.
2. Enabling interaction in real time.
3. Objects and viewpoints registered in 3D

Registration refers to the accurate alignment of the real world and the virtual content. This is facilitated through the use of various tracking technologies to monitor the movement of any object or part of the body such as the hands or handheld interaction devices, however typically it will be used to capture the position and rotation (gaze direction) of the head in six degrees of freedom (DOF), namely, the latitude, longitude and altitude of position and the corresponding yaw, roll and pitch rotations of head.

These two distinct data sets (position and rotation) are sent from the tracking sensors to the computer at discrete time intervals where they are mapped in real time onto the transformation matrix of the viewing frustum, or virtual camera, to produce alignment between the real and virtual camera. Furthermore by applying the inverse of the camera's transformation matrix to the spatially referenced virtual artifacts to be visualized, the tracking data also enables the AR system to keep them fixed within 3D space and thus remain correctly registered within the user's view of the world. This is a non-trivial task that if not successfully addressed will ruin the illusion of co-existence within the augmented environment (AE) and expose the user to the risk of motion sickness due in part to the accuracy of the human ocular system (Azuma 1997). Therefore deploying AR on a construction site, with its characteristically expansive, uncontrolled and unprepared setting, will require accurate long-range sensors and trackers, nevertheless, a shortage of such technology has been identified as one of the biggest obstacles to successful implementation of outdoor AR (Dunston and Wang 2005).

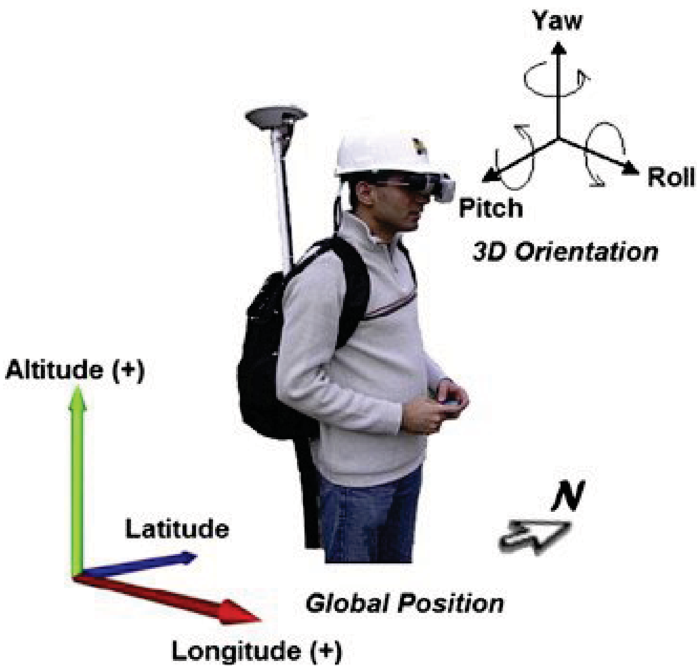

Fig. 2: A typical mobile AR setup showing the 6DOF of tracking information. (Source: Behzadan 2008)

GPS is commonly used in AR research for untethered positioning in an unprepared outdoor environment. However, despite its ubiquity within location aware computing, issues with variable positional accuracy and signal deterioration in covered or built-up environments are well documented. Compensation techniques such as Differential or Real Time Kinematic (RTK-GPS) go some way to mitigating these inaccuracies, which in the case of RTK GPS can improve accuracy to within five centimetres on the ground, although altitudinal positioning (height above mean sea level) is typically much less accurate and problems created when there is no clear line-of-sight with the sky remain a significant feature of this technology.

Inertial sensors (INS) and compass modules measure linear acceleration, rotational rates and heading information respectively through the application of gravity and the earth's magnetic field, and as such do not rely on any kind of preinstalled infrastructure or markers within the environment to be augmented. INS units typically integrate the outputs from a gyro and accelerometer to yield the physical orientation of the sensor, however whilst able to handle rapid movements they suffer from both linear and non-linear drift that accumulates over time. Conversely, modern electronic tilt-compensated compasses are reasonably accurate in use and with typical granularity of around 0.5 degrees can provide autonomous and accurate orientation tracking. Nevertheless a compass will not respond as quickly as an INS and is adversely affected by magnetic distortions caused by environmental conditions or proximity to metallic structures or equipment. However mitigation in the form of calibration routines or physical shielding of the device can lessen the effect of these environmental factors.

3.1 AR in Construction

Scientific and lab-based research efforts have continued to push back the boundaries of what is technically possible with AR as a visualization and communication medium. However successful application of these techniques to real world tasks and problems will enable the development of novel support tools that engender task-centered communication and collaboration and through contextual information delivery can enhance the work environment.

AR CAD (Dunston and Wang 2005) is a table-top AR visualization tool that uses calibrated fiduciary markers with vision-based tracking to allow real time, in-place visualization and analysis design models. Shin and Dunston have further proposed a novel approach that uses AR in a prototype structural steel column inspection tool (Shin and Dunston 2009), whilst Golparvar-Fard et al. (2009) propose overlaying time-lapsed photographs showing the as-built condition of a construction site with an as-planned 4D simulation model for construction progress monitoring.

Despite some examples of AR in construction related research, instances of 4D CAD in AR remain scarce. A4D is such a proposed system that provides an interface between the design and construction process within a Distributed Virtual Environment (DVE), however this application does not support outdoor AR, providing only a marker-based tracking and interaction paradigm within an indoor setting (Dias *et al*. 2003). While not strictly a 4D system, a further example extends previous work into construction-based discrete event simulation into an outdoor AR environment using GPS, a head tracker and a head mounted display for the contextual visualization of 3D animations of construction operations (Behzadan 2008). More recent work from VTT Technical Research Center in Finland extends upon their earlier systems by enabling interaction with BIM-based IFC files and schedule information to provide on-site AR based 4D visualization of the construction product and process using GPS, a digital compass and marker-free vision tracking (Hakkarainen *et al*. 2009).

To address cited issues with current construction planning practices and current 4D CAD approaches, whilst leveraging the strong information communication and interaction capabilities of AR, it is proposed that potential exists for an AR-based 4D planning tool (4DAR) to enable the formulation of a schedule by enabling planning team members to interact with each other whilst viewing and manipulating a unified 3D model of the proposed structure within the context of a construction site. The following section describes the approach and development of the proposed system and describes the results so far from the prototype modules that have been implemented.

4. 4DAR: On-Site Construction Planning

Previous research has highlighted the shortcomings of conventional construction planning techniques, such as the level of abstraction, the amount of information processing and the risk of multiple schedule and design interpretations leading to problems with effective communication and coordination. Additionally, current 4D CAD approaches have been shown to provide only post-planning review of a schedule that has invariably been created in the conventional manner and as such has been exposed to the problems cited with that process. In order to resolve these issues discussed above, a framework has been developed that builds upon previous work into outdoor AR, 4D CAD, collaborative planning, Building Information Modeling and model-based scheduling to provide a 4DAR prototype for interactive on-site planning.

The project is being developed using the Vizard VR Toolkit™ from WorldViz, a development environment which wraps a highly optimized OpenGL and OpenSceneGraph-based rendering pipeline in a Python scripting environment. In addition it provides support for most standard VR and consumer hardware devices and is extendible through additional python libraries. This ability to extend the functionality of Vizard through standard third party python libraries has proved invaluable when developing modules and interfaces to interact with hardware and software devices used during this project.

The proposed framework for AR4D is centered on an IFC based Building Information Model file. This information-rich model file will be utilized by the system not only as a repository of information regarding the structural attributes and relationships within the architectural model, but also as a central store for data relating to the schedule–task–component links and information. In addition, the IFC file is converted into an OpenSceneGraph (OSG) compatible file to allow it to be loaded by the chosen development platform, thus also providing the graphical input to the system.

Once the 3D file is loaded into the system the names of the objects within the model are parsed to enable the retrieval of information from their equivalent entities within the IFC file (the IFC objects' Tag number is appended to the 3D object's name). The information is then stored in relation to the object by the application to enable the development of a two-way flow of information between the 4D engine and the IFC file. While the purpose written 4D engine handles all real time interactions between the user, the model and the system.

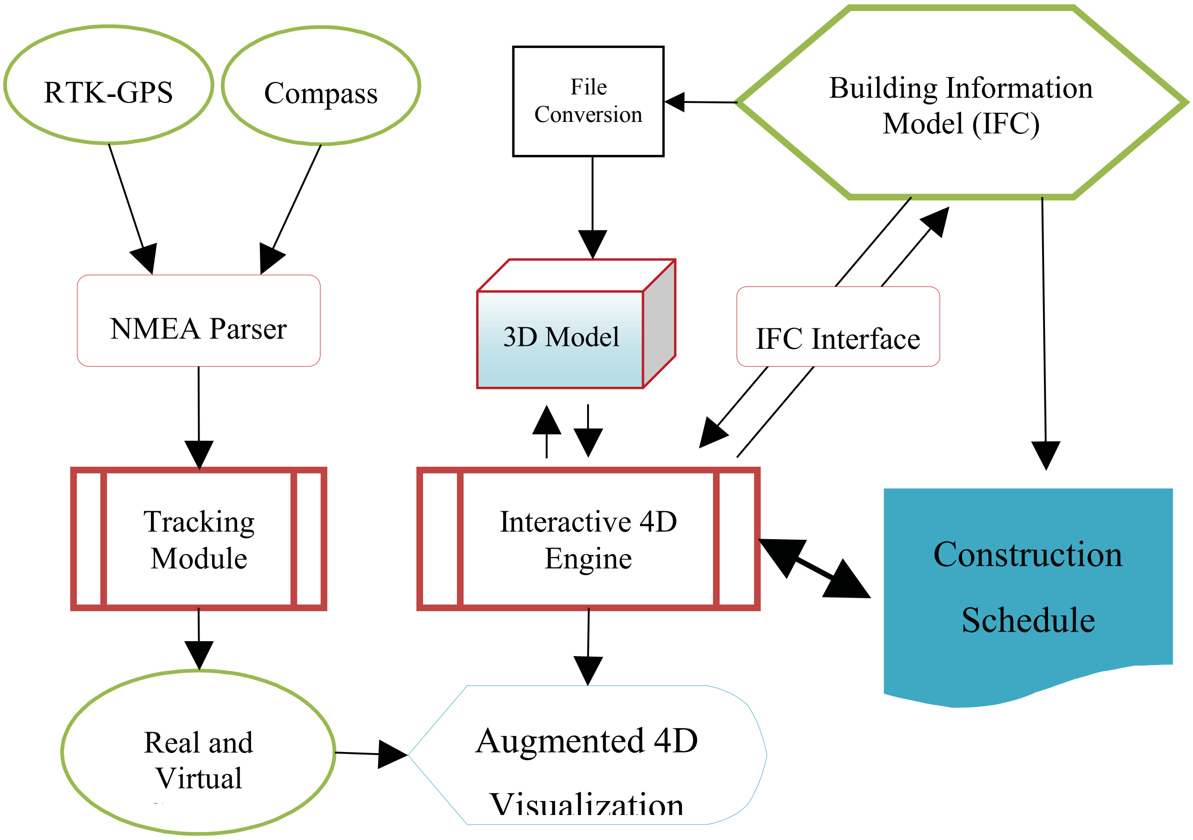

Fig. 3: The proposed framework for AR4D

Inputs for the tracking module are the positioning and orientation sensors which allow the system to keep the real and virtual content correctly positioned in relation to each other. Positioning data is obtained from a real time kinematic GPS (RTK-GPS) consisting of a static base unit that transmits corrective data to the mobile rover unit which is connected to the AR system. This global position of the system user is then transformed and projected onto the UK National Grid using the Ordnance Survey OSTN02 transformation. A tilt-compensated compass unit monitors the orientation of the user's gaze, providing the heading in relation to magnetic north together with values for pitch and roll in degrees. Both tracking sensors provide their data in the NMEA sentence format allowing instances of the same parsing module to be used for both, whilst also enabling alternative hardware devices to be used as long as they employ this standard interface.

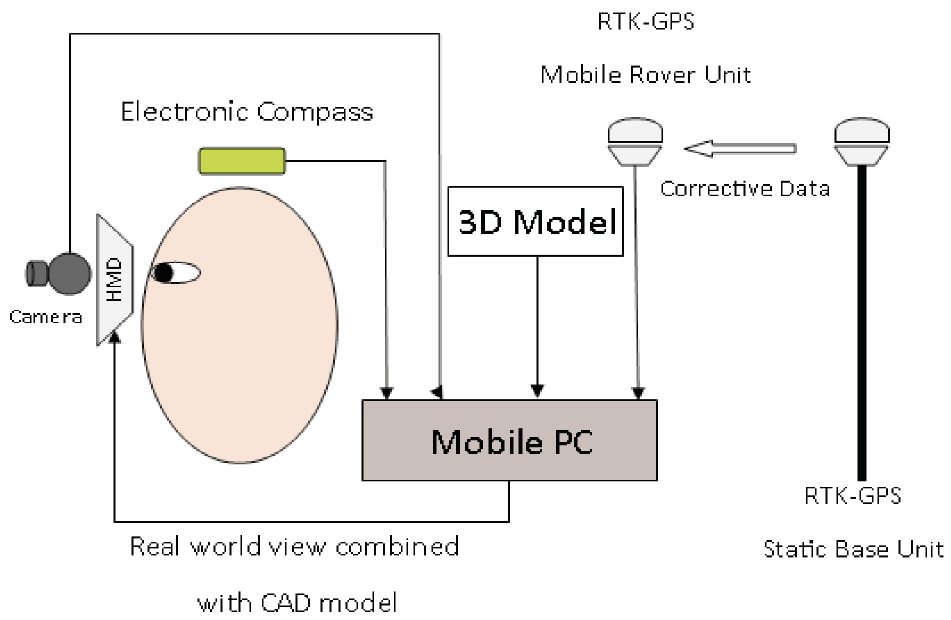

Fig. 4: The hardware configuration for AR4D

5. System Implementation

Based on the framework presented in the previous section a prototype system is under development to enable the generation of a construction schedule through interaction with a unified 3D model of a proposed building within the context of a construction site. The hardware for the project has been chosen, software modules have been written and initial tests reveal the feasibility of the proposed approach.

5.1 BIM Centric 4D

The use of semantically rich model files within AR4D is enabling the development of mechanisms to alleviate the time consuming task of individually selecting building elements (Zhou *et al.* 2009) by facilitating selection by physical or relational attributes. Using relationships and attributes defined by the BIM, elements within the IFC file can be searched for by various attributes, including building story or connecting spaces, enabling the development of various group selection mechanisms. Entities and relationships are also defined for capturing schedule information within the BIM in relation to tasks and building elements and a method is currently being tested for creating these data structures directly from within AR4D.

5.1.1 IFC

Native support for and interaction with IFC files is being enabled through the open source IFCsvr ActiveX Component, a generic IFC toolbox. This automation object is made accessible from Vizard's Python environment using the *makepy* utility from the win32com Python library. Methods are provided by the IFCsvr for reading and writing objects and attributes to and from the IFC file and these can now be accessed from the Vizard environment. Initial tests have succeeded in extracting information regarding object attributes and structural relationships. More recently the relational structures for correctly storing task and schedule information have been successfully created. Therefore schedule information could be saved back to the IFC file to facilitate its storage and its future communication.

5.1.2 AR4D Engine

Using the 3D model as an interface for schedule creation, AR4D removes the abstraction of the planning process. By selecting 3D building elements the user is able to define task dates using an on-screen calendar mechanism. The result is currently stored in a Python dictionary in relation to the corresponding building element. Once completed, or at any time during the process, the 4D simulation can be viewed within a real time graphical environment to check for sequence errors or constructability analysis. Collaborative viewing by multiple parties and a two-way link with the IFC file are features which are currently in development.

Fig. 5: Development work with the RTK-GPS system

6. Conclusions and Future Work

4D CAD has been shown to address issues with abstraction, miscommunication and misinterpretation associated with conventional planning techniques and yet to date, most examples provide only post-scheduling review. Augmented reality provides the possibility to convey complex spatial design information in an intuitive, contextual and readily understood format. To this end a new approach to 4D CAD is proposed, AR4D, that envisions the 3D model as the interface to the scheduling process to provide an on-site tool for collaborative, contextual schedule creation. Utilizing the semantics of the IFC model file is enabling the development of intelligent selection and sorting mechanisms whilst it's capability to capture schedule and task information supports its use as a complete repository of building information. Development work is on-going to finalize software modules and further develop the mechanism for two-way interaction with the IFC files. Work is also underway to bring together the chosen hardware devices into a wearable unit which will be tested on a real construction project in the near future.

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A CASE STUDY ON BIM ENERGY ANALYSIS OF BIPV BUILDINGS

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ABSTRACT: *Through a case study, this research investigated the process and accuracy of energy analysis of BIPV (Building Integrated Photovoltaic) buildings. BIM (Building Information Modeling) software tools were used in the process for modeling the BIPV buildings and carrying out energy analysis. The case study simulated the electricity production from the four BIPV panel systems of the BIPV Experimental House located in Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan and compared the simulated results with the monitored data. It is shown that reasonably good estimation of the electricity production of BIPV buildings for the design stage was obtained in the case study.*

KEYWORDS: *BIPV, Building Integrated Photovoltaic, BIM, Building Information Modeling, Energy analysis*

1. Introduction

Energy is one of the most important and pressing issues the human faces today. Global warming and restriction on carbon emissions have urged the need of actively looking for alternative or new energy sources and developing technologies of renewable clean energy, the most popular one is solar energy technology. Solar energy is one of the potentially renewable and clean energy which uses photovoltaic panels to collect sunlight, convert it into direct-current (DC) electricity and use the inverter to convert it to alternating-current (AC) for common use (Kubba, 2010). The performance of generating electricity is affected by solar radiation, solar spectrum, module temperature, solar cell electrical properties, etc. (King, et al., 2004).

BIPV (Building Integrated Photovoltaic) (Henemann, 2008) is a typical solar energy technology product that has great potential for carbon reduction for buildings. It uses architectural design method to integrate photovoltaic products, which generate electricity power from solar radiation, into building envelopes as part of building materials (Andreas, 2008). However, there are currently some obstacles for the wide adoption of the BIPV application. First, the cost of photovoltaic panels is still high. Second, a better design approach is needed for architects to effectively explore different BIPV applications in building design and arrive at a good BIPV solution for electricity efficiency. Third, more evidences are needed on the effectiveness of energy efficiency design of BIPV buildings as well as BIPV benefits to persuade the owners to favor BIPV buildings.

To address some of these issues, several research efforts have been conducted. For example, Xuan (2011) applied BIM (Building Information Modeling) technology (Eastman, et al., 2008) for modeling and analysis of BIPV buildings. Also, Maturi et al. (2010) compared the energy analysis results with the monitoring data of a BIPV system in northern Italy using data of one single day. They reported that the prediction of the PV array irradiation and the average temperature of the modules was obtained with good accuracy (-2% and +0.2%, respectively), while the power production was about 20% underestimated. In this paper, we present an investigation on the process and accuracy of energy analysis of BIPV buildings through a case study.

Nowadays, it is generally accepted by the construction industry that BIM is the most promising technology for enhancing the performance and quality of construction. BIM is a technology used to integrate a three-dimensional building model with building information through a building life cycle (National Institute of Building Sciences, 2007). Although the emerging BIM technology has provided a better design platform in 3D digital space, there is still lack of robust design procedures and BIM components of BIPV to facilitate the energy analysis and design of BIPV buildings. In this paper, the BIM process for modeling and energy analysis of BIPV buildings is studied. Also, the case study uses the BIPV Experimental House of the Industrial Technology Research Institute (ITRI), Taiwan for investigating the accuracy of BIM energy analysis by comparing the simulated values with the actual monitored data of electricity production.

2. BIM Modeling and Energy Analysis Procedure

The BIM modeling and energy analysis procedure is shown in Fig. 1. The BIM model needs to be constructed first. For a building designed using BIM, the model is constructed as the design evolves. For an existing building that does not have a BIM model, the model may be constructed based on the 2D CAD drawings of the building. Then, the building information that is needed for energy analysis is extracted from the BIM model and passed to energy analysis software. A commonly used file format for the energy analysis software is gbXML (2010), an open XML schema (XML, 2011) for facilitating the transfer of green building properties in 3D BIM models to engineering analysis software (e.g. energy analysis software). Some information related to the environment of the target building need to be set in the energy analysis software before the simulated results can be obtained. Finally, if the actual monitored data related to energy performance of the building exist, comparison between the simulated and monitored values can be conducted to assess the accuracy of the simulated results and perform a parametric study on the analysis parameters.

3. Case Study

3.1 Basic information

The BIPV Experimental House of ITRI is used to study the BIM process for modeling and energy analysis of BIPV buildings and the accuracy of the analysis. It is located in Hsinchu, Taiwan and is a reconstruction of part of ITRI's Building No. 46. The reconstruction was completed in November 2010 and the researchers at ITRI started then the collection of experimental data, including power generation conditions, solar radiation, light, temperature, humidity, and CO_2 concentration. Figure 2 shows a picture of the House and Fig. 3 shows its floor plan. Table 1 gives some basic information a bout the House. From Fig. 3, it can be seen that the interior configuration is made into two rooms, including the south room for simulating an office setting with 4 people and the north room for discussion and exhibition space.

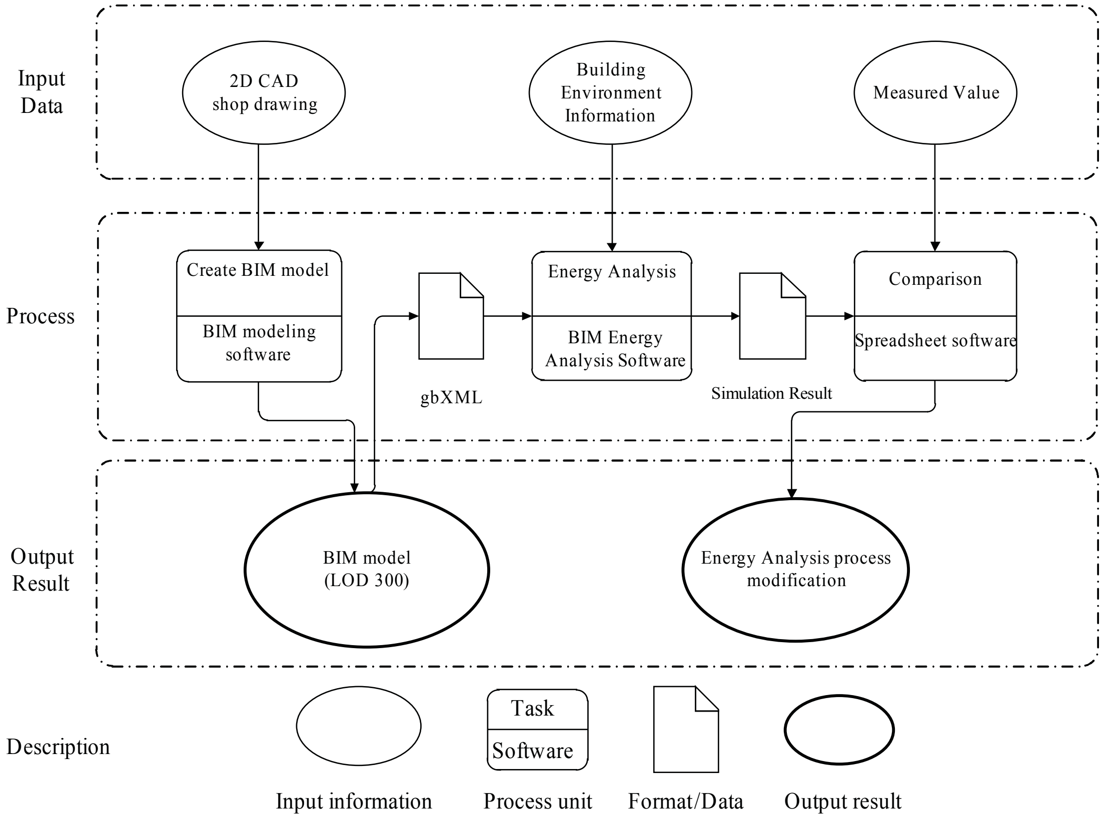


Fig. 1: BIM modeling and energy analysis procedure

Fig. 2: BIPV Experimental House.

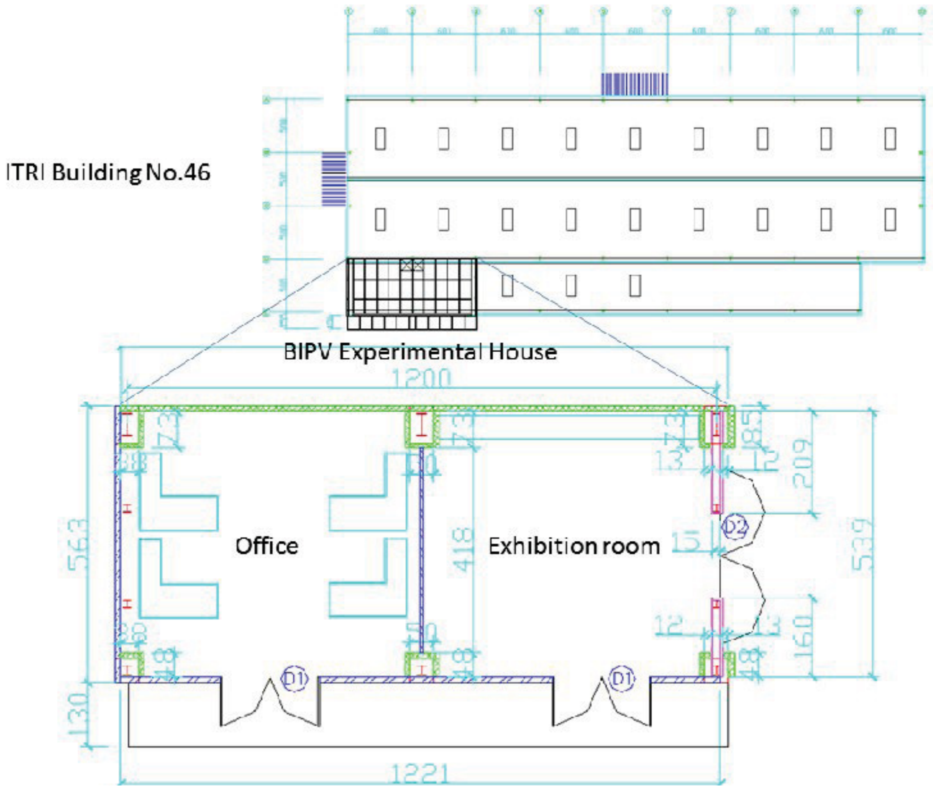


Fig. 3: Floor Plan of BIPV Experimental House

Table 1: Basic Information of BIPV Experimental House

Location	**Building. 46, No.195, Sec. 4, Zhongxing Rd., Zhudong Township, Hsinchu County 310, Taiwan (R.O.C.)**
Coordinate	Latitude 24.775°N Longitude 121.0453°E
Floor Areas	65 square meters
Dimensions	42.20°
Operation Hours	Monday to Friday 8:00~17:00
Altitude	121 meters
Working Temperature	27˚C

3.2 Modeling

Because the same series of BIM software often have better interoperability, we selected the Autodesk BIM series software, which is also a popular BIM solution in Taiwan, for BIM modeling and energy analysis in the case study:

1. Revit 2011 series (Architecture, Structure, and MEP) for modeling the BIPV Experimental House.
2. Ecotect 2011 for energy analysis of the BIPV Experimental House.

We used Revit Architecture to construct the architectural model of the building, especially the building shell, Revit Structure to construct the structural components for the building, and Revit MEP to construct the mechanical and electrical components, including the solar panels, of the building. To simulate the BIM design of BIPV buildings, Level of Development (LOD) 300 (AIA, 2008) was chosen as the level of details for BIM model construction. Figure 4 shows the shaded BIM model of the BIPV Experimental House. For modeling the areas of BIPV panels for energy analysis, the "curtain wall" object in Revit was used because it allows the convenient definition of the whole area of panel assembly and then the area can be easily divided into individual panel area. Also, for modeling BIPV panels explicitly in the BIM model, we defined a parametric BIPV component model based on the build-in solar panel object model in Revit MEP so that different types of BIPV panels can be easily constructed at the same geometric location of the corresponding "curtain wall" by setting different sets of property parameters (see Fig. 5).

Table 2: BIPV Module Information

System Number	1	2	3	4
System Position	Sloping Roofs	Right Side	Transom	Sun Shield
System Capacity (Wp)	4200	1890	750	1200
Module Type	Light-Through (Glass-Cell-Glass)	Frameless opaque modules (Glass-Cell-White Tedlar)	See-Through High Color Rendering (HCRI) Frameless module (Glass-Cell-Glass)	Frameless opaque modules (Glass-Cell-Glass)
Conversion Efficiency	11.19%	12.79%	5.24%	8.39%
Module Size (mm) L*W*H	1760*1066*11	1657*991*5	1300*1100*7	1300*1100*6.8
Rated Power (Wp)	210	210	75	120
Number（set）	20	9	10	10

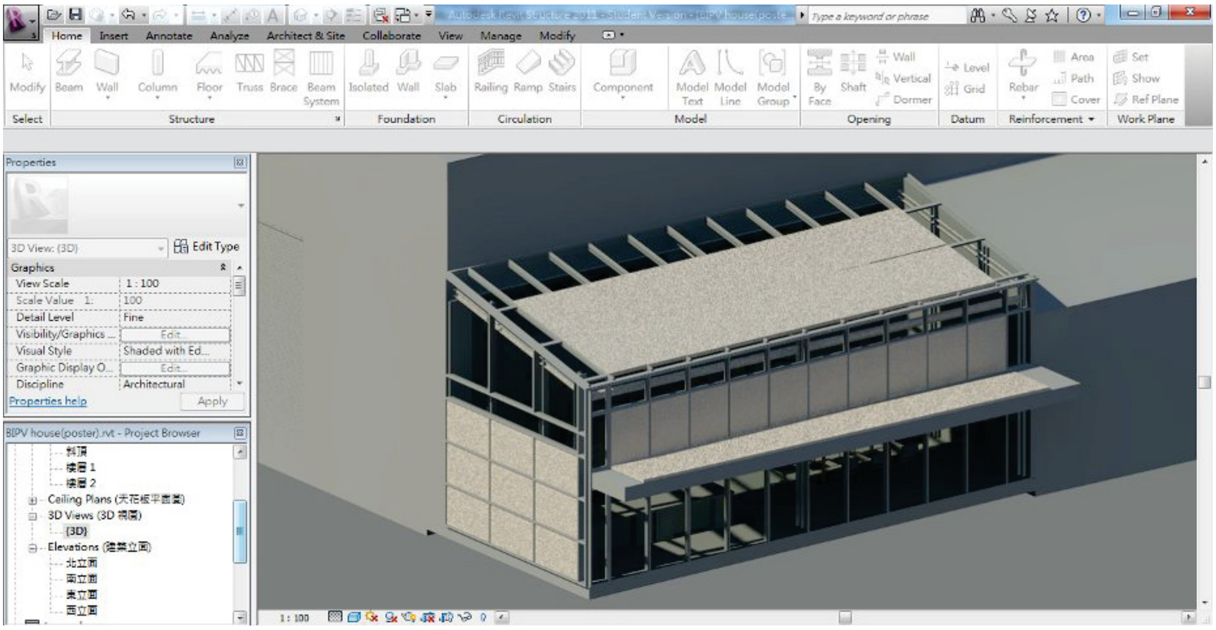


Fig. 4: BIM model of the BIPV Experimental House.

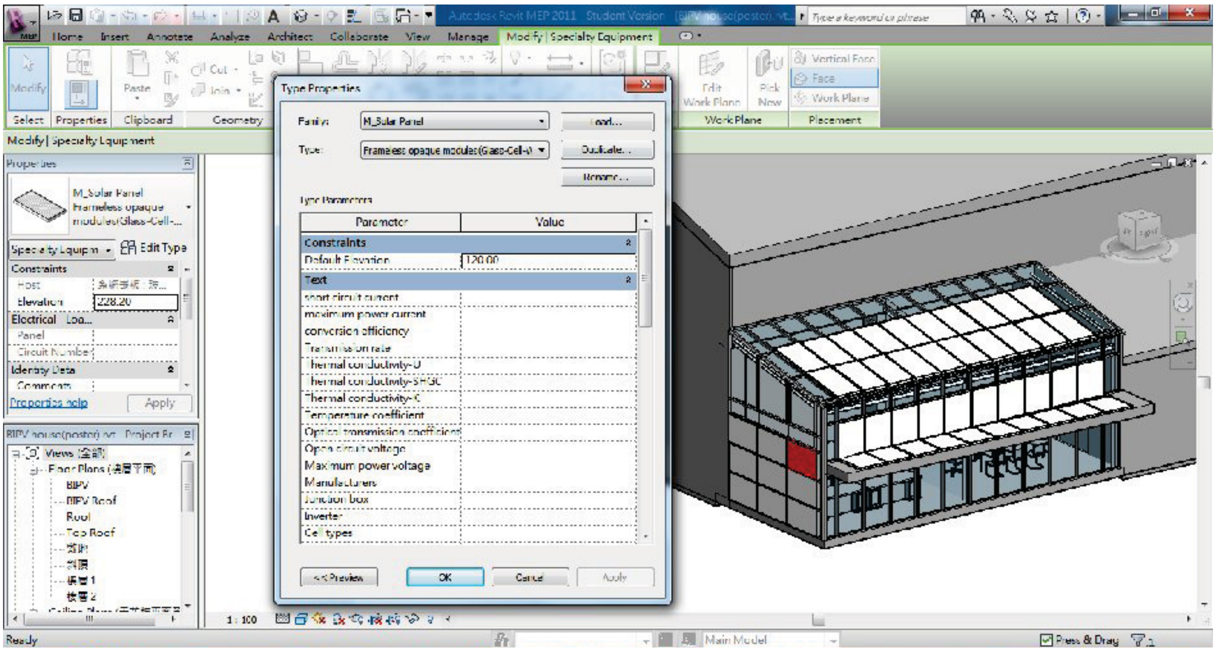
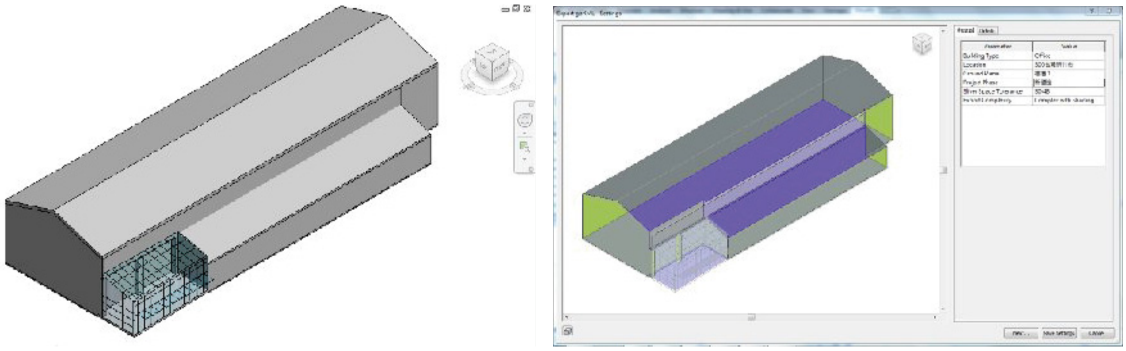


Fig. 5: Property table of the parametric BIPV model

3.3 Energy analysis

For performing energy analysis on the BIPV Experimental House, we need to output the model from Revit to Ecotect. After trying several file formats supported by both Revit and Ecotect, we found that none of them allowed complete model transfer. However, because the most important model features we would like to preserve during the transfer are building geometry and surface area information, the gbXML format was finally selected. All other formats tried, such as ifc, fbx, 3ds, and dxf, have problems of correctly preserve either building geometry or building surface area information, or both. Figure 6 shows both the Revit BIM model and the transferred gbXML model of the BIPV Experimental House.



(a) BIM model in Revit (b) Preview of output model in gbXML

Fig. 6: Transfer of BIM model of the BIPV Experimental House to gbXML format.

The following steps were carried out to simulate the electricity production of BIPV panels of the BIPV Experimental House in Ecotect:

- Prepare the ".wea" weather file that defines weather pattern information. For the case study presented here, daily solar radiation is the key information to be defined. Two sources of monitored solar radiation data were used: (1) data recorded by the actinometer installed at the BIPV Experimental House and (2) data recorded by the total weather station of ITRI, including recorded values of every hour on the hour and peak recorded values within an hour for 24 hours. In addition, direct and diffuse solar radiations should be defined respectively.
- Load in the model of the BIPV Experimental House from the corresponding gbXML file.
- Load in the corresponding ".wea" file.
- Set basic project information, e.g. project time zone, project coordinate, project coordinate, project north offset, etc.
- Assign values of conversion efficiency (as shown in Table 2) for BIPV panels.
- Compute total radiation (see Fig. 7) and hourly solar collection (see Fig. 8) of BIPV panels.

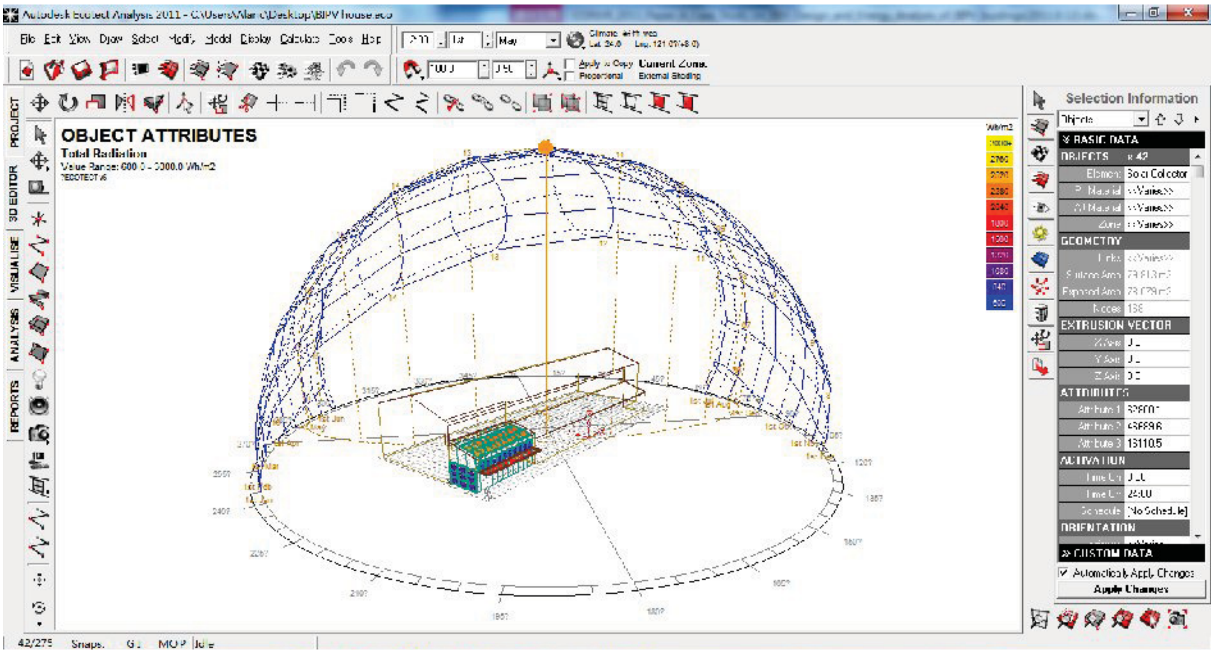


Fig. 7: Ecotect simulation of solar radiation collection for BIPV panels.

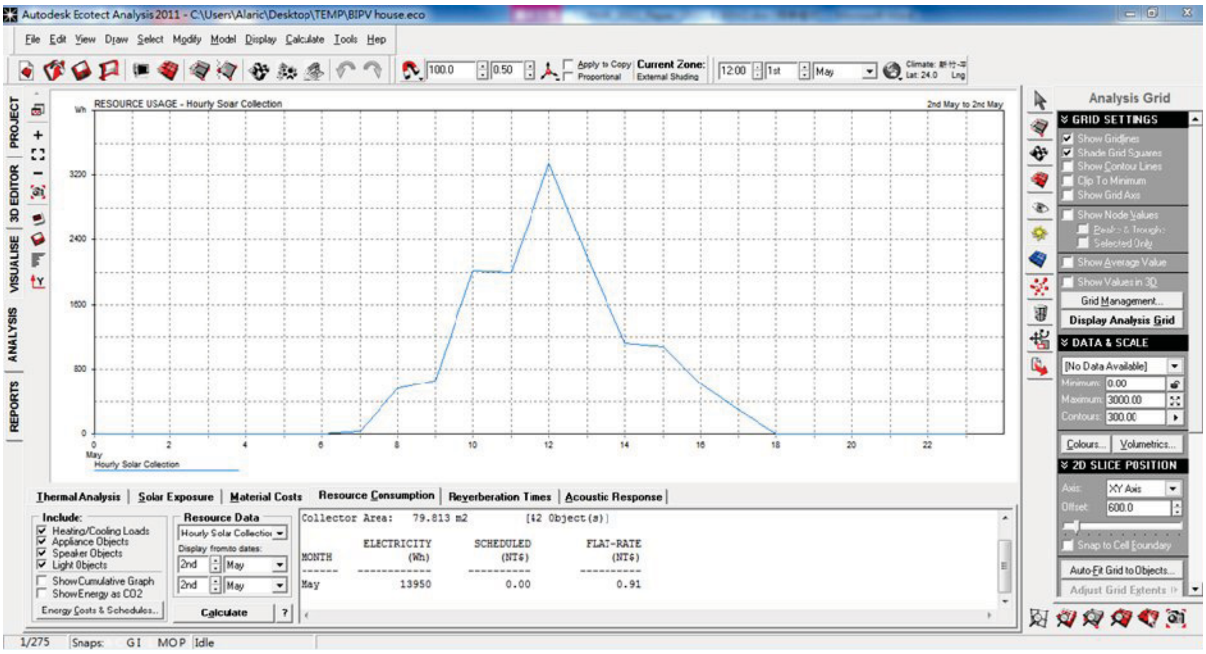


Fig. 8: Ecotect simulation of solar panel electricity production.

3.4 Results and discussions

Figure 9 shows comparison among different monitored solar radiation values using the data recorded by the actinometer and the total weather station of ITRI on May 1st, 2011 as an example. It is assumed that all the monitored solar radiation data represent only direct solar radiation (i.e. no diffuse radiation) and the conversion efficiency of each BIPV panel is not affected by the temperature of the BIPV module. Figure 10 shows comparison of simulated and monitored (or measured) electricity production values (kilowatt-hour). It can be seen that the values simulated using the data recorded every hour on the hour from actinometer and the total weather station are very close, while the actual measured electricity production value falls between (and close to the average of) the value computed using the radiation data recorded every hour on the hour and the value computed using the peak recorded value within every hour.

Figure 11 compares the measured electricity production values with those from Ecotect simulation on everyday electricity production for May 2011, using the average of the radiation data recorded every hour on the hour and the peak recorded value within every hour. Again, only direct solar radiation is considered here. It can be seen that the current simulated results match quite well with the monitored ones although the effects of solar panel temperature and the diffuse radiation have not been considered.

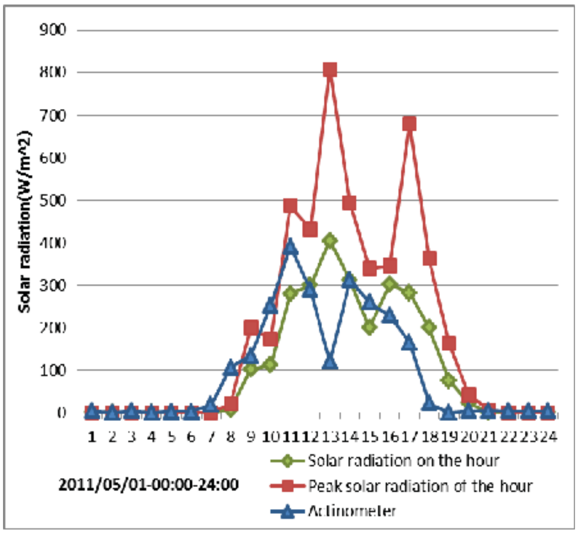


Fig. 9: Comparison of recorded solar radiations on May 1st, 2011

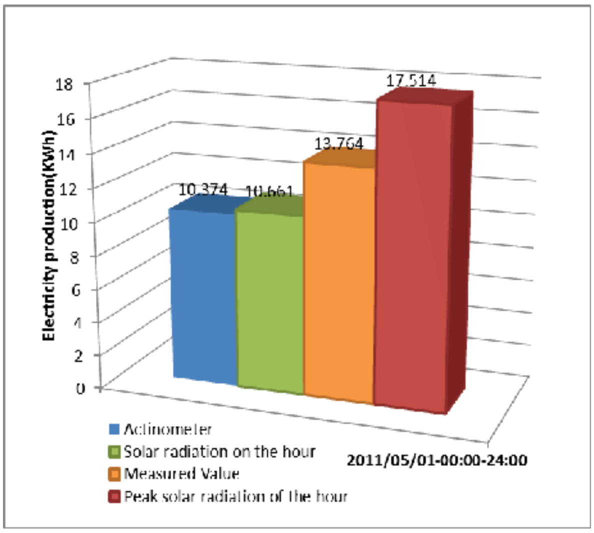


Fig. 10: Comparison of simulated and measured electricity production data on May 1st, 2011.

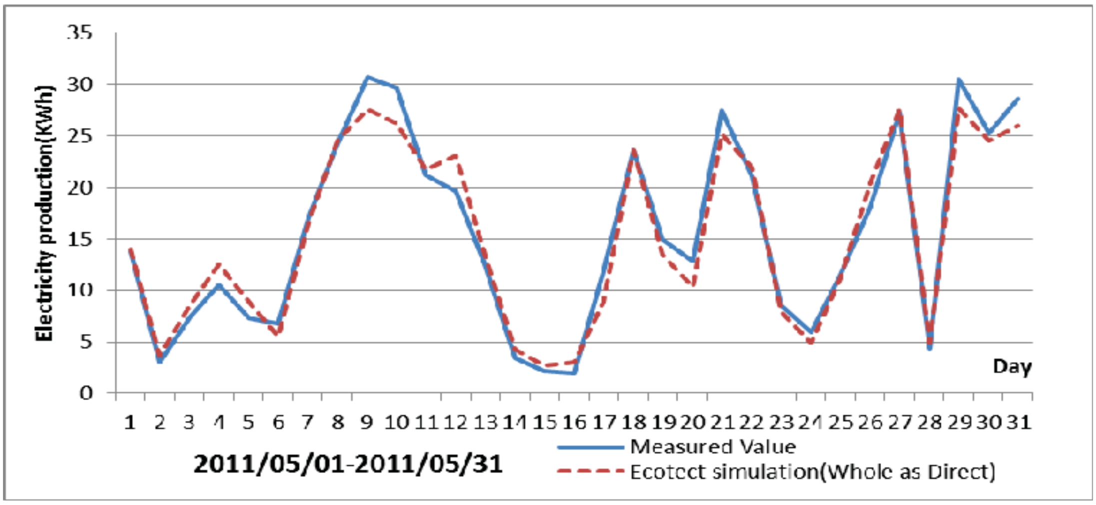


Fig. 11: Electricity production data for one month (May 2011)

For studying the effect of diffuse solar radiation, we applied the Berlage formula (Wang, 2000) to divide the recorded solar radiation values into two components, namely direct and diffuse radiations:

$$I_{suntot} = I_d + I_{diff} \quad (1)$$

$$I_d = I_0 \cdot P^m \cdot \cos i \quad (2)$$

$$I_{diff} = \frac{1}{2} I_0 \cdot \sinh \cdot \frac{1 - P^m}{1 - 1.4 \ln P} \cdot \cos^2(\frac{\theta}{2}) \quad (3)$$

in which I_{suntot} is the total solar radiation; I_d and I_{diff} are the direct and diffuse solar radiations, respectively; *P* is atmospheric transmission factor and is set to be 0.7 in this study; $m = 1/\sinh$ and h is the sun's altitude angle. By dividing Eq. (2) with Eq. (3), we have

$$I_d / I_{diff} = P^m / \frac{1}{2} \cdot \frac{1 - P^m}{1 - 1.4 \ln P} \quad (4)$$

Figure 12 shows the comparison of solar radiation collection of different BIPV panels on May 1st, 2010, as an example. It can be seen that, in this case, the consideration of diffuse solar radiation gives closer results to the measured results. It is observed that the central part of ITRI building No. 46 may block the direct sunlight on the sun shield PV system in the afternoon and the transom system is perpendicular to the horizontal surface. This is probably the main reason why these two systems are easily affected by diffuse solar radiation.

Figure 13 shows the comparison of electricity production results between the measured (or monitored) result and Ecotect simulations, including one considering only direct radiation and another considering both direct and diffuse radiations. It can be seen that, in the case of May 1st, 2011, the consideration of diffuse solar radiation gives higher electricity production value. However, if we further consider that the conversion efficiency of a BIPV panel would drop when the temperature of the panel rises, the electricity production results simulated by Ecotect would decrease.

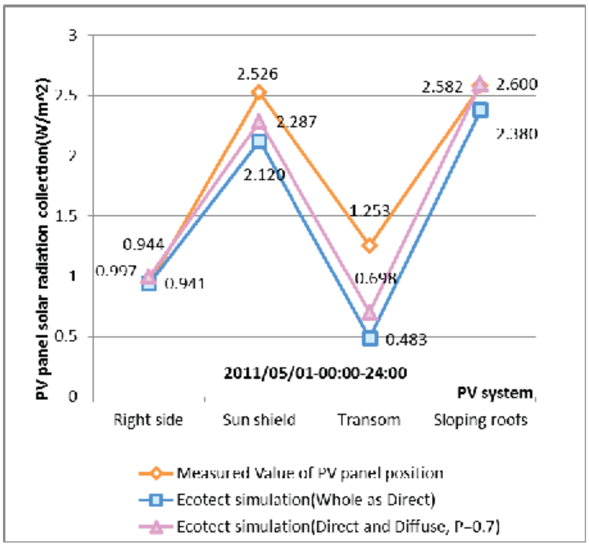


Fig. 12: Comparison of solar radiation collection of different BIPV panels on May 1st, 2011.

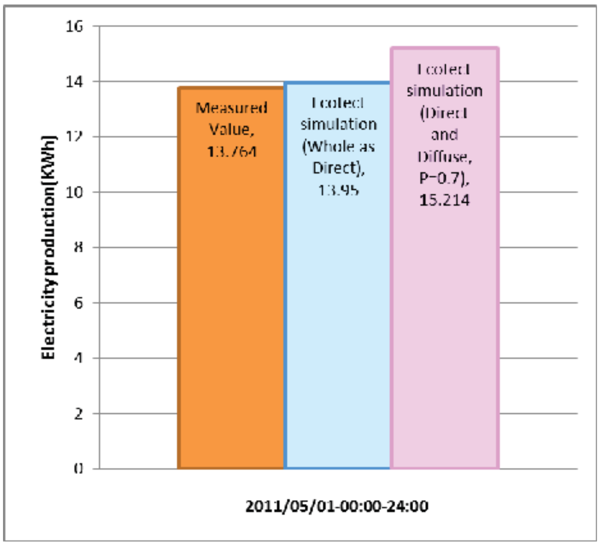


Fig. 13: Electricity production of BIPV panels on May 1st, 2011.

4. Conclusions

In this paper, we have presented a successful process for BIM modeling and energy analysis of BIPV buildings using Autodesk software series. Also, we have investigated the accuracy of energy analysis using Ecotect for architectural design. Based on the case study performed, it is found that reasonably accurate results on electricity production of BIPV panels can be obtained when we use, as an input, the average value of the radiation data recorded every hour on the hour and the peak recorded value within every hour; and consider only direct solar radiation in the analysis. More case studies should be carried out to further investigate if the results obtained in this case study can be generalized and if or when more factors, such as diffuse solar radiation and panel temperature, should be considered.

5. Acknowlegement

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BENEFITING FROM THREE DIMENSIONAL INFRASTRUCTURE DESIGN AND CONSTRUCTION MANAGEMENT

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ABSTRACT: *With the rapid development of computer hardware and continuous improvement of building information modeling (BIM) supported software tools, more and more architecture, engineering and construction (AEC) projects have already migrated or are planning to migrate from 2D-based business processes to 3D ones. 3D computer modeling can help engineers to understand and identify problems from the design stage to the construction stage more effectively than traditional methods. With 3D models, problems such as design errors, operation delays and the added cost of revisions in construction have more opportunities to be identified in a timely manner. This paper focuses on the application of 3D technologies for the North Light Rail Transit (LRT) project located in the downtown area of Edmonton, Canada, involving the construction of three stations, underground utilities, and sewer and LRT tunnels. Various visualization technologies have been applied in this large-scale, multi-disciplinary project. Autodesk® AutoCAD® Civil 3D®, BIM-based utility design software, was adopted for underground modeling and constructability review. A 4D construction model was developed in Autodesk® Navisworks® for project-level control, and a 3D animation-capable tunneling operations simulation model was established in the Construction Synthetic Environment (COSYE) developed at the University of Alberta for analyzing the tunneling processes of the storm tunnel. In the 3D animation federate (a component of the tunnel federation), 3D stratigraphy was integrated to provide soil conditions for the simulation model. The application and discussion of the 3D technologies are depicted in detail in the paper. The application of 3D technologies enabled intuitive, accurate and comprehensive representation of design details and the construction plan and more realistic operations simulation, which provided a promising complement for ensuring on-time, on-budget project delivery.*

KEYWORDS: *building information modeling (BIM), virtual reality, utility design, constructability review, animation, discrete-event simulation, stratigraphy*

Introduction

With the rapid development of computer hardware and continuous improvement of building information modeling (BIM) supported software tools, more and more architecture, engineering and construction (AEC) projects have already migrated or are planning to migrate from 2D-based business processes to 3D ones. 3D computer modeling can help engineers understand and identify problems from the design stage to the construction stage more effectively than traditional methods (Morad and Beliveau 1994; Kang et al 2007). With 3D models, problems such as design errors, operation delays and added cost of revisions in construction have more opportunities to be identified early (Danso-Amoako et al 2003). This paper focuses on the application of 3D technologies for the North Light Rail Transit (LRT) project located in the downtown area of Edmonton, Canada. The North LRT is a 3.3 km extension starting from the existing downtown Churchill LRT Station to the Northern Alberta Institute of Technology (NAIT). It involves the construction of a tunnel from Churchill Station to MacEwan Station in the downtown area, three LRT stations (MacEwan, Kingsway and NAIT), roadways, a drainage tunnel, track, catenary, electrical right of way, communications, and LRT signals. The North LRT line is scheduled to open in 2014 and the total budget is estimated at $725 million. Various visualization technologies have been applied in this large-scale, multi-disciplinary project. Autodesk® AutoCAD® Civil 3D®, BIM-based utility design software, was adopted for underground modeling and constructability review. A 4D construction model was developed in Autodesk® Navisworks® for project-level control, and a 3D animation-capable tunneling operations simulation model was established in the Construction Synthetic Environment (COSYE) developed at the University of Alberta for analyzing the tunneling processes of the storm tunnel. In the 3D animation federate (a component of the tunnel federation), 3D stratigraphy was integrated to provide soil conditions for the simulation model. The application and discussion of the 3D technologies are depicted in detail in the paper. The application of 3D technologies enabled intuitive, accurate and comprehensive representation of design details and the construction plan and more realistic operations simulation, which provided a promising complement for ensuring on-time, on-budget project delivery.

The remainder of this paper is organized as follows: First, we review previous research efforts related to construction management in 3D and operations simulation. Then, we elaborate the details of the application of 3D utility design and constructability review, 4D modeling and simulation-based animation for the North LRT project. Finally, our findings, the potential limitations of current computer tools, and suggestions for future practices are presented and discussed.

2. Literature Review

2.1 Constructability Review in 3D

3D modeling and virtual reality technologies have been applied to access constructability issues before real construction work is conducted, which would help identify conflicts and clashes between different disciplines, reduce rework, and prevent construction accidents (Haque and Rahman 2009). Hartmann and Fischer (2007) applied 3D/4D models in a transit center project in New York City for constructability review, which facilitated design and construction communication and problem identification. Chi and Kang (2010) developed an integrated physics-based dual crane erection simulation system, which can automatically generate crane motion paths in a visualization environment. Sampaio et al. (2010) demonstrated several 3D and VR applications for rehabilitation, maintenance, and representation of construction processes and construction methods. Akinci et al. (2002) proposed a 4D WorkPlanner Space Generator, which can automatically generate project-specific work spaces in a 3D environment and can be linked to a time schedule, enabling time-space analysis prior to construction. Shah et al. (2008) proposed a 4D visualization model which can automatically generate terrain surfaces and progress profiles for earth work by integrating road design and cut and fill data. Sacks et al. (2010) applied lean construction concepts and proposed a KanBIM system, which is a BIM-based construction management system based on the Last Planner System. Benefiting from the integrated product model, KanBIM holds the potential to enable effective and efficient communication and negotiation. In addition, augmented reality technologies have been applied to monitor the real life progress of projects. They gather daily progress photographs along with geographic information, then overlap the as-built data on the as-planned 4D model to indicate construction progress (Kazi et al.

2009; Kim and Kano 2008). Kraus et al. (2007) indicates that for underground utility construction the early identification of interference of the existing and proposed utilities is critical for timely project delivery.

2.2 Animated Construction Operations Simulation

Construction operations simulation provides an effective way to analyze detailed construction operations using Monte Carlo simulation. Compared to tedious statistics tables or various kinds of charts, 2D or 3D animated simulation results can help users understand the interactions of activities and resources. A great body of research has been conducted to implement simulation driven animation, from the iconic 2D animation to the realistic 3D animation. In order to verify and validate the simulation results, Zhang et al. (2002) proposed a 2D iconic animation. VITASCOPE, developed by Kamat (2003), is a generic visualization tool which enables spatially and chronologically accurate 3D visualization of specific construction operations. It tracks the simulation outputs from STROBOSCOPE using a time trace file, then animates the 3D objects that are imported from VRML (Virtual Reality Modeling Language) files. Kamat and Martinez (2001) presented an earthmoving case to demonstrate VITASCOPE. Taking earth moving as a case study, Rekapalli and Martinez (2011) proposed the concept and implementation of concurrent animation, with which users can interact with the animation during the course of a simulation run. Thus, it provides a more realistic virtual world for users to experiment with different working conditions. Al-Hussein et al. (2006) established a simulation-based crane lifting animation using MAXSCRIPT, which is a scripting language for Autodesk® 3ds Max®. Sharing the same idea, Manrique et al (2007) proposed an animation for complicated residential tilt-up-panel structures. Unfortunately, due to the discrepancies between operations simulation and animation, the generation of animation is time consuming and lacking efficiency (Manrique et al. 2007). In order to overcome the limitation, a high level architecture (HLA)-based framework is proposed to facilitate the integration of operations simulation and animation (Zhang et al. 2011).

3. Utility Constructability Review

BIM-based design tools are becoming more and more popular in AEC sectors. However, most pilot projects are building projects which adopt BIM tools for building architecture, structure, and MEP (Mechanical, Electrical and Plumbing) design. The application of BIM in utility design is still rare. A lack of successful application cases, availability of BIM-enabled design tools, or a traditional contracting strategy might be the reasons that hinder the adoption of a BIM solution in utility design and construction management. For the North LRT project, the utility design and construction involves designing new utilities, relocating some existing utilities and abandoning other existing utilities across a very large area. The utilities were designed by multiple design consulting companies and include a sewer line, electrical line, gas line, water line, traffic signal line, communication line, and duct banks for traction power and communication. Traditional design methods using 2D drawings were adopted from the very beginning. When it came to the construction stage, the project manager found that the identification of interference between underground utilities was a big issue. Due to the complexity of the underground utility lines, it is very hard to determine the potential conflicts by interpreting utility plan drawings and cross section drawings, even by very experienced engineers. However, if potential interferences are left to the field workers, this will probably cause construction delays, potential accidents and huge amounts of capital loss. Thus, the project team decided to adopt visualization technologies to figure out the problems prior to construction.

The idea is to establish 3D models for all the underground utilities, catenary pile foundations, and building foundations in the most congested three station areas according to the utility design drawings as shown in Fig 1. Then, specific checking rules are applied to the 3D models to identify potential interferences. After investigating the available software tools on the market, Autodesk® AutoCAD® Civil 3D® was selected as the most appropriate tool for utility modeling and interference checking. The sewer and sanitary network modeling feature in Civil 3D® provides a parametric interface to establish 3D pipe lines and sewer and sanitary structure (e.g. man hole, catch basin) models. Various types of pipe and structure can be picked from the built-in part list. Users can also define customized parametric pipe or structure parts using the part builder. The typical process to create the 3D utility model consists of several steps. First, ensure or define the pipe or structure parts in the part list. Then, convert the utility centerline, which is usually a spline in AutoCAD on the plan drawing, to a feature line. A feature line can both keep the alignment of a utility and allow the adjustment of elevation at designated control points. The elevation information is usually provided by cross section drawings or data tables. It can be input to the feature line object using the feature line editor. The feature line integrates the information on the plan and cross section drawings. Finally, the utility parts can be created from the feature line as design. The parametric modeling tool significantly reduces efforts required to create utility 3D models, compared to traditional 3D modeling methods in AutoCAD®. In the North LRT project, the most difficult work in utility modeling is to gather the required elevation data. The elevation data is provided either by cross section drawings or scattered hydrovac points. For other utility lines which usually fall out of the range of cross sections or are parallel to the cross sections, no elevation data is ready to use. In this case, we need to consult the designer to get the elevation data by other means or to use their best judgments or estimations. In order to make the use of network modeling feature in Civil 3D®, utilities other than sewer and sanitary such as gas lines or electrical lines are treated as sewer or sanitary lines and the flow direction is ignored.

The first interference report was generated by analyzing the 3D underground utility models for Kingsway station. About 15 potential problems have been identified, which can be dealt with in several ways. (1) Ignoring. The 3D model shows some existing utility intersects with other existing utilities. However, the real interference does not exist. It might be caused by inaccurate utility data, or utility relocations which have not been filed. (2) Adjustment on site. Some minor utility conflicts can be easily fixed on site. (3) Design revision. One major issue that was found is a proposed duct bank which intersects with several existing and proposed utilities. One of the major issues is shown in Fig. 2.

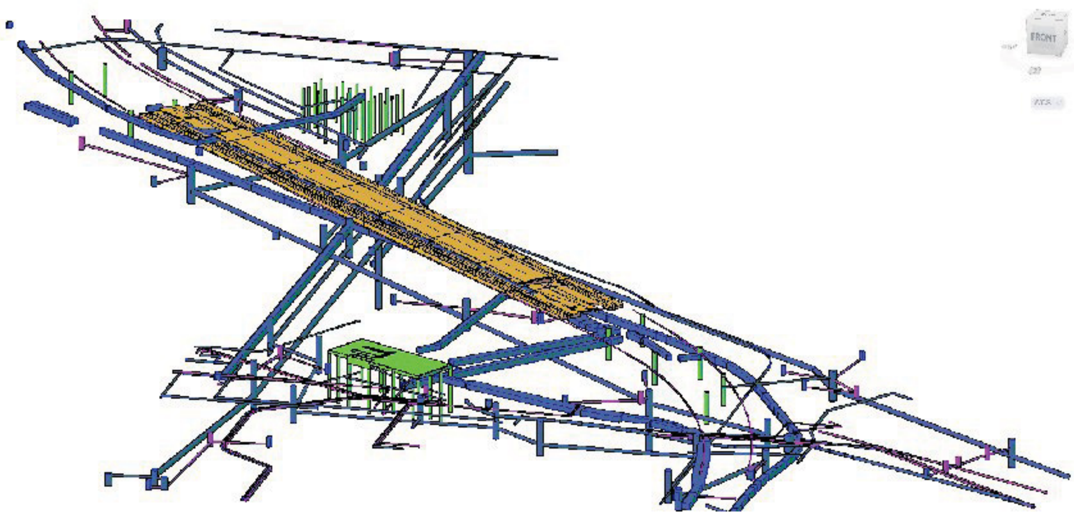

Fig. 1: 3D utility model of Kingsway station

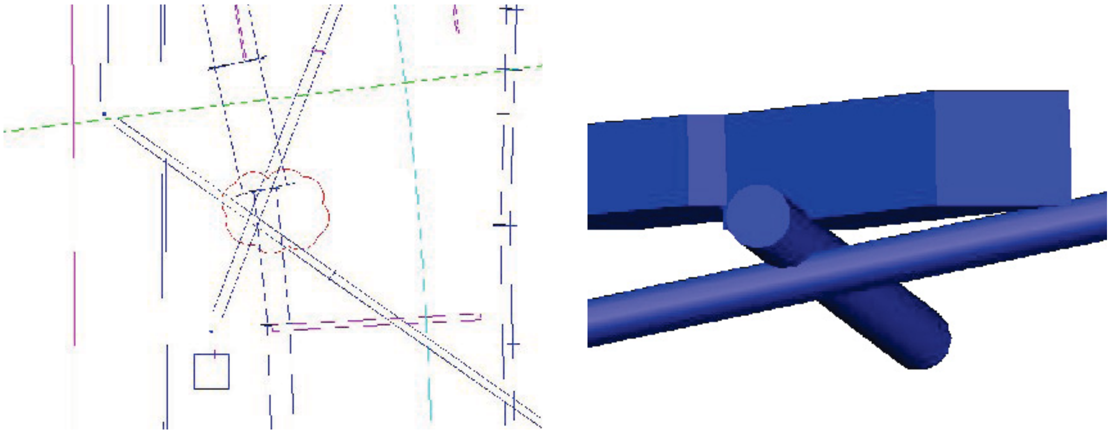

Fig. 2: A duct bank intersects with the existing and proposed sewer line

The 3D models successfully helped the project team identify potential constructability issues. The early adoption of BIM-based utility design is suggested for future projects. The project team can not only benefit from interference checking, but also improve the productivity and accuracy of construction documentation.

4. 4D Construction Planning

A 4D model was developed in order to facilitate project-level construction planning. Autodesk® Navisworks® was adopted as the commercial 4D software tool for the North LRT project. Generally, 3D modeling work is time-consuming and labor-intensive. However, fully developed 3D models which were established for an effect animation covering tunnel and portal, stations, track, catenary, and roadway were ready to use in this project. The models in Autodesk® 3ds Max® can be easily exported to NWC file formats using the NWC exporter, and then imported by Navisworks®. Using the NWC format, which is a native file format in Navisworks®, can keep the most information in the original models. In order to facilitate the manipulation of 3D models in Navisworks®, they are organized in multiple files according to different disciplines.

At the early stage of construction, only a baseline schedule was provided in Oracle® Primavera P6. It was loaded via the Time Liner in Navisworks®. In order to associate the 3D models with their corresponding activities in the schedule, 3D Models were grouped together using selection sets. Selection sets serve as a bridge between 3D components and activities. There are two means to establish a selection set: (1) picking up components on screen; and (2) using a search condition against properties of components. The advantages of using search condition to build up a selection set is that the selection set will stay up-to-date when new 3D components are added later. However, compared to the models that are derived from BIM-based software tools, the 3D models that are derived from 3ds Max® have less informative properties. The selection sets were therefore built up using the first means for the project. Specific matching rules (matching activity names with the names of selection set) can be applied to selection sets and activities to establish the associations. Then the 4D model is ready to reflect the construction schedule as shown in Fig. 3.

Several limitations have been identified during the application. Firstly, not all activities have corresponding 3D components ready to use. For example, only utilities within the three station areas have been modeled. This problem might be alleviated if a BIM solution is adopted from the design stage. Secondly, for some activities such as site preparation, excavation, backfill, fire protection etc., 3D models are hard to build as these activities represent processes, not physical components. In this case, texture images and color schemas might be able to apply to corresponding areas. Thirdly, the current tool doesn't support earned value analysis (EVA). An add-on is under development to provide more informative data in the 3D environment.

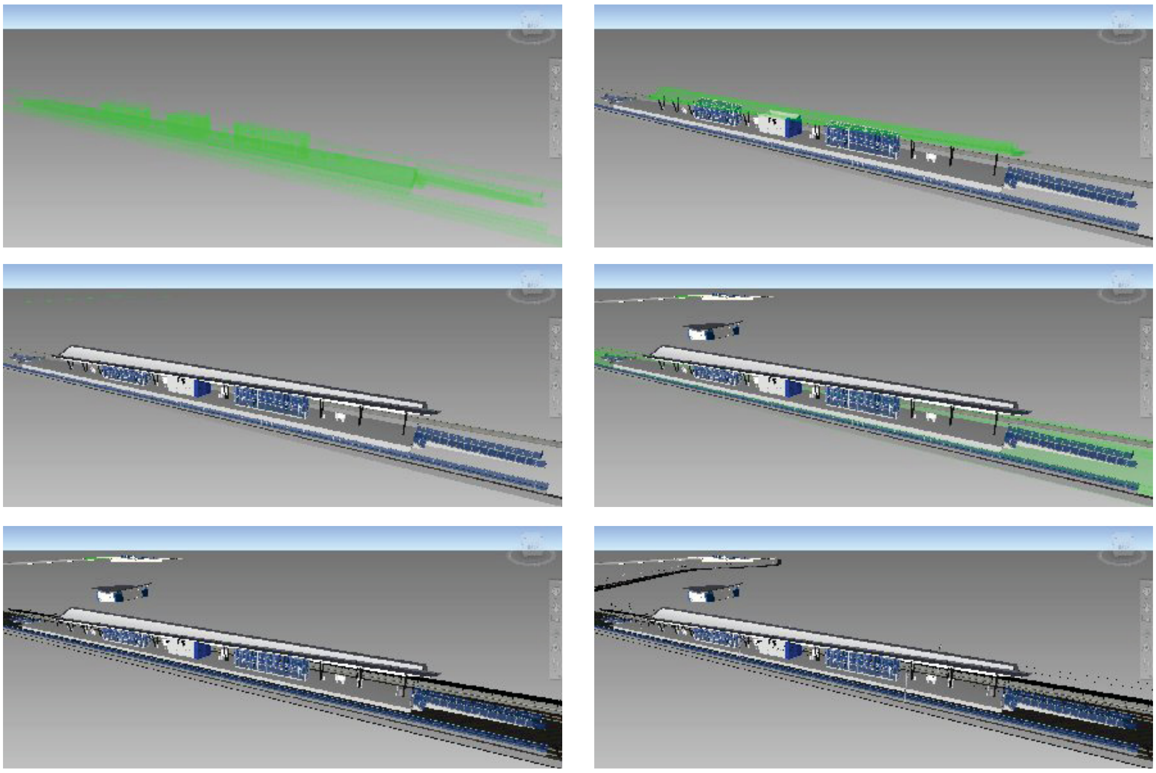

Fig. 3: Construction sequences of Kingsway station

5. Simulation-Based Tunneling Visualization

As the 4D model is built up on the Critical Path Method (CPM), it can only provide a panorama view of the overall project, lacking the capability to analyze repetitive activities with complicated resource interactions. Operations simulation was adopted to analyze the construction of the drainage tunnel of the North LRT project. It provides a way to experiment with various construction scenarios by considering uncertainties, resource constraints, space limitations, and so forth. In the research, a tunnel operations simulation model is established using the tunnel federation in the COSYE framework (Zhang et al. 2010). In the distributed simulation environment, the tunnel federation integrates discrete event operations simulation, geographic information on Google Maps™, and 3D tunneling animation with geological information.

The map federate is designed to visualize the current location of excavation during a simulation on the Google Map. The Google Maps™ API (Application Programming Interface) was used to implement the federate. It receives the current chainage of the tunnel boring machine. The chainage is a double value measuring the distance along with an alignment from a predefined start point. Then it converts the chainage to a GPS (Global Positioning System) coordinates according to the designed alignment of tunnel. A land marker is updated on the map reflecting the changing excavation locations as shown in Fig. 4.

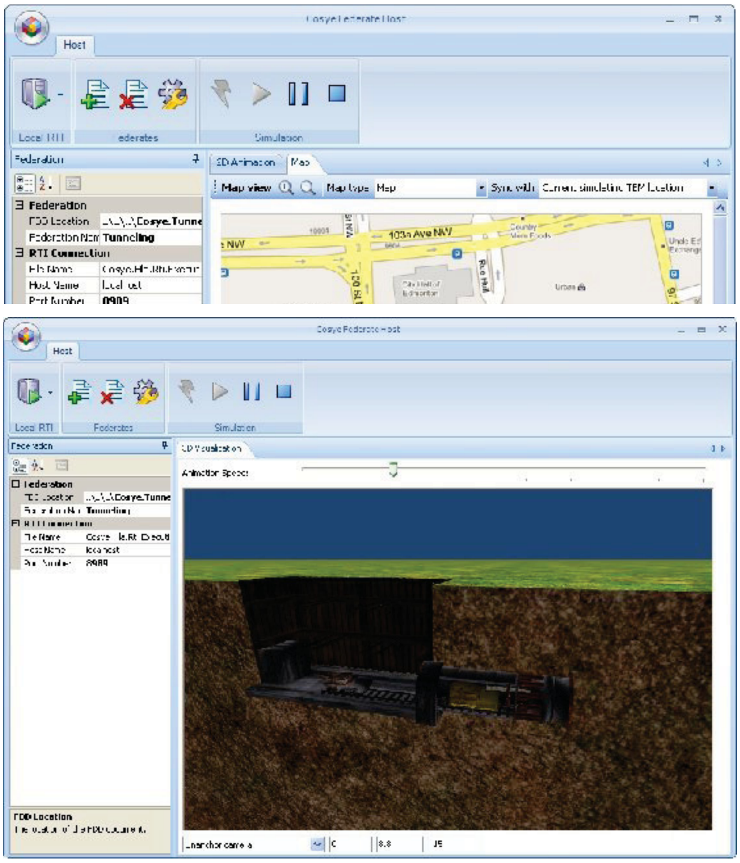

Fig. 5: 3D tunneling animation

The 3D animation federate is designed to visualize the tunneling processes under simulation in a 3D environment as shown in Fig. 5. It incorporates the tunnel shaft 3D model, tunnel 3D model, boreholes, 3D strata generated from professional geological software, and the 3D resource model including TBM, train and crane, providing an intuitive and vivid way to observe the construction activities being undertaken. During simulation, the 3D animation federate also serves as a data provider of soil conditions. Soil condition has a big impact on the penetration rate of TBM. Thus, it will affect the productivity of tunnel construction. Real time soil condition publishing allows the simulation engine to access the latest soil condition and then use it to adjust simulation parameters.

6. Conclusions

Virtual reality and operations simulation are a powerful combination for planning and tracking construction in a large-scale project such as this LRT extension. The 4D model provides a project-level representation, and the operations simulation model is capable of producing operations-level analysis. Both of the technologies have been proven to be valuable aids to construction management for large-scale complicated projects. The BIM-based solution for utility design is recommended for adoption from the very beginning in future projects. It is believed that the project team will benefit from the innovative design and construction management technologies.

7. Acknowledgements

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KINESTHETIC AND STEREOSCOPIC VISION FOR CRANE TRAINING SYSTEMS

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ABSTRACT: *Crane operation training has to be appropriate and sufficient enough to mitigate an important cause of fatal casualties on construction sites – unsafe and incorrect crane operation. However, the large physical space and costs associated with setting up an actual construction environment for training purposes can be prohibitive. In recent times, investigators have started utilizing virtual reality technologies to provide trainees with a low risk and low cost albeit realistic training environment. Reducing the differences between operating cranes in the real world and the virtual environment can increase the effectiveness of training programs. Stereopsis and motion parallax are important factors which enables trainees to experience higher levels of realism and intuitiveness within virtual training environments. This research proposes the use of kinesthetic and stereoscopic vision methodology to improve crane training systems based on the mechanisms of human visual perception. Kinesthetic and stereoscopic vision simulates the relationship between the various physical movements of a person with the person's view. In our system, the primitive elements of human vision, which include stereopsis and perspective, are presented on the display and change according to the relative motion between the screen and the user. Through this proposed mechanism, the trainee's vision varies according to his/her position, and realistic spatial information retrieval methods are enabled. The trainee is able to localize lifted objects and examine the surroundings of the lifted objects intuitively using head motion. The developed interaction mechanism realistically simulates the critical relationship between crane operators and their surroundings, thus providing trainees with highly effective off-the-job training experience.*

KEYWORDS: *crane simulator, physics-based simulation, motion parallax, crane training, stereopsis, kinesthetic, interactive visual simulation.*

1. Introduction

Cranes are some of the most versatile and helpful machines on construction sites (Hanna and Lotfallah, 1999). The function of cranes is to erect heavy objects and lift them to their installation locations. For instance, in the construction of facilities and buildings, cranes are used to transport or install structural material, such as massive reinforced bars, members of precast reinforced concrete structures, structural steel columns or beams, and other material. In addition to erecting structural material, the setup of precast façade components or heavy equipment, such as curtain wall systems and large-scale mechanical equipment, often need to be established using crane operations. In the transportation industry, parts of freight transport tasks also rely on efficient crane operations. Since cranes are very advantageous and necessary to the construction industry, several crane-related issues must be addressed. One of the critical issues is crane safety, because crane-related accidents are one of the major causes of construction fatalities (Beavers et al., 2006).

Crane erection tasks are highly risky components of the construction process. The specifics of crane operations can vary quite widely depending on the complexity of the construction project. During the erection process, crane operators must be keenly aware of the crane's situation and loading limitations (Neitzel et al., 2001). The Center for Construction and Training (CPWR) (2009) reported that 632 worker deaths involving 611 crane accidents occurred in the U. S. from 1992 to 2006. This report also indicated that the lack of worker training was a key cause of fatalities. In fact, it is well known in the construction industry and research that one way to decrease construction injuries is through effective worker safety and health training (Goldenhar et al., 2001). Beavers et al. (2006) also pointed out that many crane-related workers have insufficient training, and suggested that the workers should be adequately qualified before they commence any work involving cranes. In order to reduce crane-related accidents, it is believed that effective training for crane operators should be implemented with fidelity.

In Taiwan, according to the Regulations for Labor Safety and Health Education and Training (2009), employers must equip their employees who work with cranes with sufficient safety and health education for at least three hours within every three years. However, current training scenarios are usually over-simplified and are conducted with limited equipment due to costs and difficulties in arranging realistic training conditions which replicate a real construction site. Thus, an operator is usually unable to receive sufficient off-the-job practice time in a realistic training environment that replicates the complex environment of a real construction site.

Researchers have studied crane-related accident issues since the 1970s (Hakkinen 1978). Shepherd et al (2000) introduced a taxonomic analysis of crane fatalities in the USA, and classified more than 500 recorded crane-related accidents into several types. Neitzel et al. (2001) also reviewed crane safety in the USA and suggested related solutions for the construction industry. Other studies have suggested that analyzing and measuring the factors affecting site safety as quantitative assessments can improve the safety performance of crane-related construction projects (Shapira and Layachin 2009; Shapira and Simcha 2009a; Shapira and Simcha 2009b). Shapira et al. (2008) suggested that the use of a vision system to assist the use of tower cranes may improve safety performance. Furthermore, Kang et al. (2009) suggested the use of 3D simulation and visualization for simulating the erection process of steel structures. They believe that using 3D simulation to rehearse the construction process in a virtual environment can help crane operators to understand the complex operation processes involved. However, although previous research in the area of cranes has been extensive, not much research has focused specifically on improving the training aspect.

In order to provide low-cost and effective training environments for crane operators, researchers have started utilizing virtual reality and game technology to simulate crane training environments. Huang and Gau (2003) developed a mobile crane simulator to provide trainees with an immersive and physical operation environment. The simulator was equipped with a six-manipulator motion platform to simulate the acceleration and vibration situations of a real crane. They also provided an operational panel and simulated certification exam scenarios using multi-screen displays. CMLabs (2007) and GlobalSim (2007) have developed training simulators with real-time physical behaviors and realistic visualization. These products also provide immersive environments for trainees using multi-screens, simulated cabins, and operational sticks.

However, these studies and products have not considered the important differences between human vision behavior in the real world and in a virtual environment, an important factor which influences the realism of the operating environment. For instance, precise depth perception can help trainees to comprehend three-dimensional scenes using two-dimensional images projected by display devices. Furthermore, trainees cannot change their point of view using body movements to avoid the obstruction of lines of sight at certain viewpoints to comprehend the space relationship between objects. These are natural behaviors of a crane operator during actual operation on a construction site.

Importance of Precise Visual Perception

Precise and accurate vision simulation is an important factor in crane training because crane operations must be monitored carefully by crane-related workers using their vision in actual complex environments. Actual crane-related operations are generally cooperative work performed by crane operators, signalmen, and riggers. During crane operations, these crane-related workers must confirm the correctness and safety of crane operations from their various respective viewpoints. In order to correctly operate according to an erection path and to avoid dangerous events (such as boom collision, load impact, and electrocution), operators must examine operation conditions in a three-dimensional environment using their visual perception of depth. In human vision, the precise way to perceive depth information is *stereopsis*.

Stereopsis is a process by which the relative depth of two objects is perceived according to the differences between two projected images from a viewed scene; this process exists with binocular depth perception. For human vision, binocular disparity, the difference between images acquired from each eye, can be compelled to obtain depth perception by stereopsis (Wheatstone, 1838). For virtual crane operation, stereopsis plays a critical role because correct and safe operation includes the unmistakable spatial cognition of static and moving objects with keenly manual control. Several studies have revealed the importance of stereopsis in training and education. Luursema et al. (2008) used computer-implemented stereopsis for virtual anatomical learning and found that computer-implemented stereopsis not only benefitted surgery training, but also improved spatial cognition skills for anatomical learning. Furthermore, Mazyn et al. (2004, 2007), found that stereopsis plays a necessary role in developing and using compensatory cues for depth perception when people practice interceptive actions, especially under temporal constraints.

The report by McKee and Taylor (2010) found that binocular depth thresholds are significantly superior to monocular depth thresholds, whether an observed object is isolated or surrounded by other reference objects with textured surfaces. Hence, the lack of stereopsis is likely to lead to the loss of precise depth perception, even though the surrounding textured objects can provide depth cues such as shading, relative sizes, occlusion, or other monocular depth cues. These are also given by general display media such as TVs, pictures, screens, and other two-dimensional media, but lack the cues for stereopsis.

Other experiments also revealed the essentiality of stereopsis for depth perception in the wide range of observed distances. Allison et al. (2009) processed experiments and found that human stereopsis is effective for discriminating depth and distance estimation from the personal interaction space to at least 18 m. Palmisano et al. (2010) indicated that the estimation of depth relied only on stereopsis at large observation distances from 20 m to 40 m. These experiments show that stereopsis is a critical process in depth perception from the personal interaction space to large distances, which encompass the conditions that a crane operator usually works in.

Similar to surgery, correct and safe crane operation requires accurate information of geometric relations between objects. However, current virtual crane training systems do not enable trainees to perceive geometric and space relations in natural ways such as binocular depth perception and varied viewpoints according to body or head motion. Therefore, in this research, we propose the use of kinesthetic and stereoscopic vision for virtual crane training systems. This allows trainees to develop operating skills with natural and intuitive visual perception. In other words, the display of a training environment can dynamically shift views according to the trainees' displacement and also provide stereoscopic binocular images to enhance the realism of training systems.

3. Kinesthetic and Stereoscopic Vision Methodology

Kinesthetic and stereoscopic vision is a control methodology that allows observers to experience realistic 3D visual perception using body motion in a virtual environment. Kinesthetic and stereoscopic vision describes the dynamic relationship regarding how an observer interacts with a virtual world using body motion as with the real world. The methodology includes two parts: stereoscopic vision and kinesthetic vision.

3.1 Stereoscopic vision

We used the stereoscopic vision method to add binocular cues for trainees, with the method basically following the principle described by Wheatstone (1838). Fig. 1 demonstrates the basics of stereoscopic vision, in which the points o and o' are at different distances from the projected screen. From the screen, each eye sees different projected points from the same observed point, such as point o, and we find that the parallax *p* of the observed point o is a function relative to the distance *d* and s as follows:

$$p = i\frac{d}{s+d} = i(1-\frac{s}{s+d}) \qquad (3\text{-}1)$$

where *i* is inter-ocular distance. Based on this relationship, we can determine the parallaxes of the projected pixels from each vertex of an object in a virtual environment, and then generate the relevant binocular images on screens.

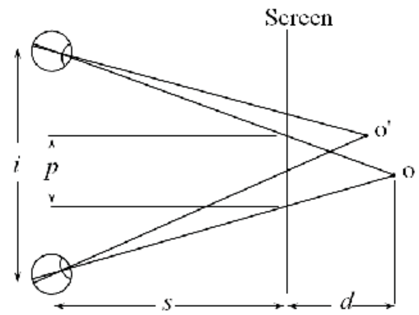


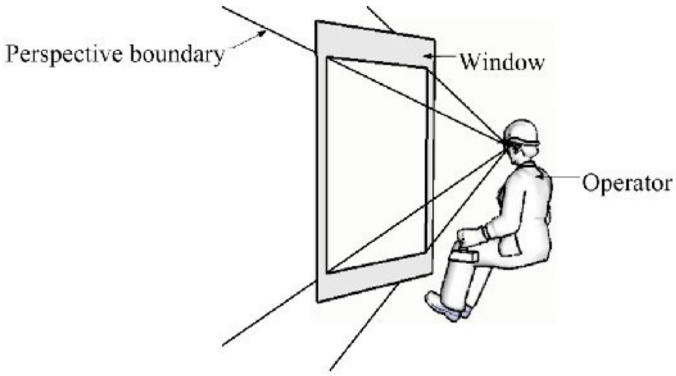
Fig. 1: The principle of stereoscopic projection (modified from Wheatstone, 1838).

3.2 Kinesthetic vision

Kinesthetic vision enables trainees to experience motion parallax from screens, allowing them to examine the surroundings of crane operations in virtual environments from different viewpoints while they try to move their heads laterally.

In order to achieve kinesthetic vision, we developed the kinesthetic perspective transformation, which converts the geometry of an operator perspective frustum (Fig. 2) to a virtual eye frustum. This is done so that trainees can view a virtual scene according to their eye position, making it as realistic as viewing an actual scene of a construction site through cabin windows. This mechanism supports a 3D perception process in addition to stereopsis. Another way to perceive 3D information through human vision in daily life is to view a scene from different viewpoints according to different observers' positions. This provides visual cues called *motion parallax*, which is the relative displacement of viewed objects caused by a change in the positions of observers (Cutting, 1986). This visual cue enables operators to examine environments from different viewpoints, which is important for perceiving spatial information from complicated 3D geometry such as on construction sites. For crane operators, the perspective is constrained by the construction site and operation environments, and the constraint varies according to the relative displacement of the environment and operator positions.

Fig. 2 illustrates the perspective constraint caused by a cabin window, and Fig. 3 demonstrates constrained perspective in a simple scenario. In the demonstrated scenario, the scene changes according to the trainee's position because the perspective boundary transforms according to the trainee's position. The lines in Fig. 2 represent the perspective boundary, which clip the visible range through the window, and with obstacles causing some areas to become hidden. For instance, in Fig. 3(a), the area within the perspective boundary constrained by the window is depicted by zone ofd. However, due to obstruction by the steel structure, the visible zone only includes zone ofe and zone oca, while zone bced is a blocked-view zone. In this occasion, the worker is in the visible zone ofe and can be seen by the operator (Fig. 3(a)). For Fig. 3(b), the perspective boundary is changed drastically because the operator is displaced to the right. The visible zones include oigh, oje', and oc'a'. The worker is in the blocked-view zone b'c' and e'd' because according to the operator's vision, he is being obstructed by the structure (Fig. 3(b)). Thus, from the demonstration, we can discern the importance of motion parallax, especially on complicated construction sites. The operator usually intuitively moves his head to examine the surroundings carefully to ensure operational safety.



The operators' perspective is constrained by the window frame, and therefore the boundary of the perspective forms a frustum shape behind the window.

Fig. 2: The perspective boundary of an operator viewing through a window.

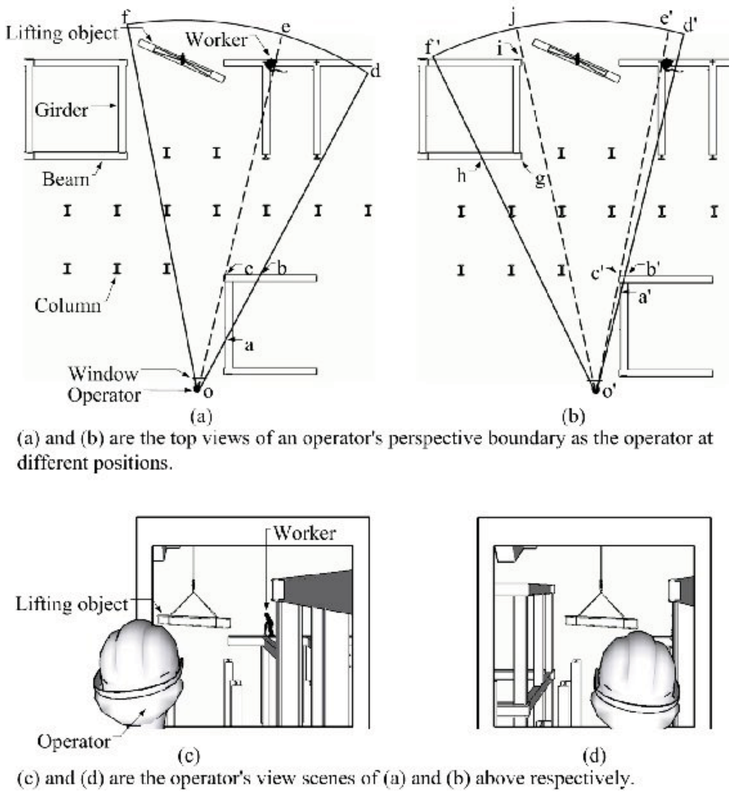
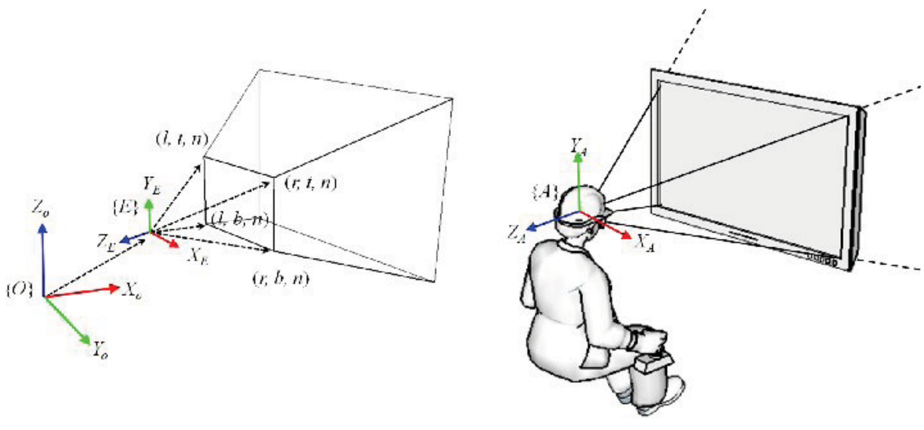


Fig. 3: The dynamic nature of the perspective boundary during crane operations.

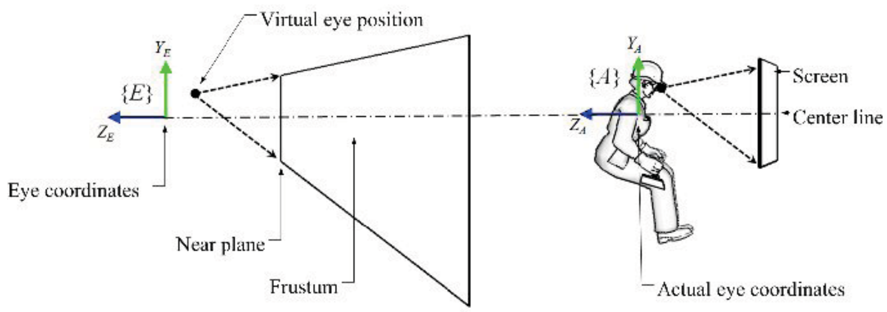
The kinesthetic perspective transformation was developed in order to reach the goal whereby a trainee can view different scenes on a screen from different positions, similar to viewing scenes from a window. The concept of this transformation is illustrated in Fig. 4. Eye coordinates {*E*} (Fig. 4 (a)) represent the perspective volume (also called the frustum) of a virtual camera (or a virtual eye) in a virtual environment {*O*}. If objects are within the frustum, they will be projected to the near plane in directions to the eye coordinates' origin. In fact, the projected images from the near plane will be presented on a screen and will be watched by a trainee who is located at the actual eye coordinates {*A*} (Fig. 4 (b)).



(a) (b)

Fig. 4: The concept of kinesthetic perspective transformation uses (a) a virtual eye perspective to imitate (b) a trainee's perspective by synchronizing the ratio of their geometric shapes.

In the general display method, the perspective frustums are always symmetrical and static. If a viewer's face is normal to a screen and is at the screen's center line through the screen surface, the watcher will receive approximate realistic scenes without distortion. However, for crane training, in order to deliver realistic spatial information similar to that of reality, the frustums must dynamically deform according to the trainees' eye position so that trainees can accurately receive the scenes from different viewpoints. Therefore, the vectors (*l*, *t*, *n*), (*r*, *t*, *n*), (*l*, *b*, *n*), and (*r*, *t*, *n*) in Fig. 4 (a) are relative to eye coordinates {*E*} and define the shape of the frustum dynamically. For instance, Fig. 5 (a) shows that the virtual eye frustum deforms with a trainee's perspective frustum (Fig. 5 (b)).



(a) The right side view of the deformed perspective frustum.

(b) The right side view of a trainee who watches the screen with a displacement to the center line.

Fig. 5: A diagram of eye coordinates in a virtual world and in reality.

The kinesthetic perspective transformation modifies the modelview matrix and the projection matrix in the computer graphics pipeline. These are rewritten as follows:

$$M'_{modelview} = M_{modelview}\begin{pmatrix} 1 & 0 & 0 & (-{}^{A}P \times X_A)W_E / W_A \\ 0 & 1 & 0 & (-{}^{A}P \times Y_A)H_E / H_A \\ 0 & 0 & 1 & (-{}^{A}P \times Z_A)D_E / D_A \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

where $M'_{modelview}$ is the modified modelview matrix, and $M_{modelview}$ is the general modelview matrix; ^{A}P is the eye position in actual eye coordinates $\{A\}$; X_A, Y_A, and Z_A are unit vectors that represent the X, Y, and Z axis in $\{A\}$; W_E is the width of the near plane, and W_A is the width of the screen view; H_E is the height of the near plane, and H_A is the height of the screen view; D is the distance from the origin in eye coordinates to the near plane or the screen center. Their index E and A represent the virtual eye space and the actual world.

Then, the modified projection matrix is written as follows:

$$M'_{projection} = \begin{pmatrix} \frac{2\rho D_E}{W_E} & 0 & -2\frac{^{A}P \times X_A}{W_A} & 0 \\ 0 & \frac{2\rho D_E}{H_E} & -2\frac{^{A}P \times Y_A}{H_A} & 0 \\ 0 & 0 & \frac{-f-\rho}{f-\rho} & \frac{-2f\rho}{f-\rho} \\ 0 & 0 & -1 & 0 \end{pmatrix} \quad (2)$$

where $M'_{projection}$ is the modified projection matrix; f is the far plane distance; and:

$$\rho = -1 + \frac{^{A}P \times Z_A}{D_A} \quad (3)$$

In short, kinesthetic perspective transformation converts the actual eye perspective to the virtual eye perspective by introducing the modified modelview matrix and the projection matrix into the computer graphics pipeline. The variable of this transformation is the actual eye position ^{A}P. According to ^{A}P, the modified transformation matrices simultaneously vary and adjust the projected scene to a corresponding viewpoint.

4. Implementation

To implement the proposed virtual crane training system, we integrated the Microsoft XNA framework and NVIDIA PhysX to develop a virtual environment for trainees as shown in Fig. 6 (b) and (c). The XNA is a framework for game development and includes 2D texture and 3D model rendering with advanced shader effects, audio effects, and user inputs. The dynamic physics effects and behaviors are simulated using NVIDIA PhysX, a well-known physics engine for generating a realistic visual physics experience. For the physical interaction environment of the crane training system, we used a 50" 3D TV, a game console controller, and an Xbox 360 Kinect sensor as major interaction equipment. These are shown in Fig. 6 (a).

For stereoscopic display implementation, we used the NVIDIA 3D Vision toolkit. This toolkit supports active stereoscopic display devices and provides stereopsis cues of consistent quality from every view angle, a necessary feature for crane operation trainees.

In order to implement kinesthetic vision in real-time, a trainee's eye position must be detected and delivered to the training system. Since our eyes' positions are always fixed on our heads, we used a Kinect sensor (Fig. 6 (a)) in this implementation to capture the head position as ^{A}P (mentioned in *section 3.2*).

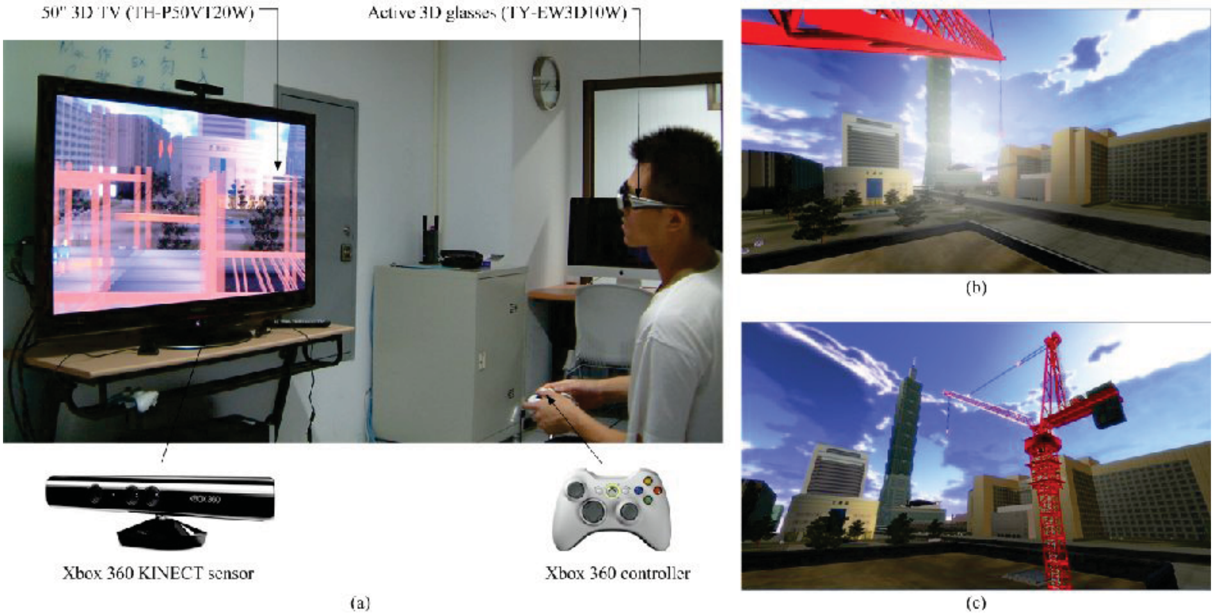


Fig. 6: (a) The interaction environment, (b) the operator view from a cabin room, and (c) the modified environmental scene from an actual urban scene in Taipei City, Taiwan.

To simulate the crane in the virtual environment, we implemented the physics-based crane model developed in previous studies (Hung and Kang, 2009). The physics model of the crane was constructed as a multibody which consisted of multiple rigid bodies connected using joints. Each rigid body has its own properties, such as mass and collision boundaries, and behaves according to the laws of physics in a virtual environment. Each rigid body in a physical model represents a model part which can transform (including rotation, translation, or scaling) individually and is constrained by joints. Fig. 7 shows the defined physics model of a virtual luffing crane.

The simulation results show that the proposed kinesthetic and stereoscopic vision method for crane training is intuitive and easy for human control, thereby replicating natural crane operating behavior in the real world. The stereoscopic method can deliver realistic vision perception experiences. This can reduce incorrect operation and judgment caused by insufficient information on space and geometric relations.

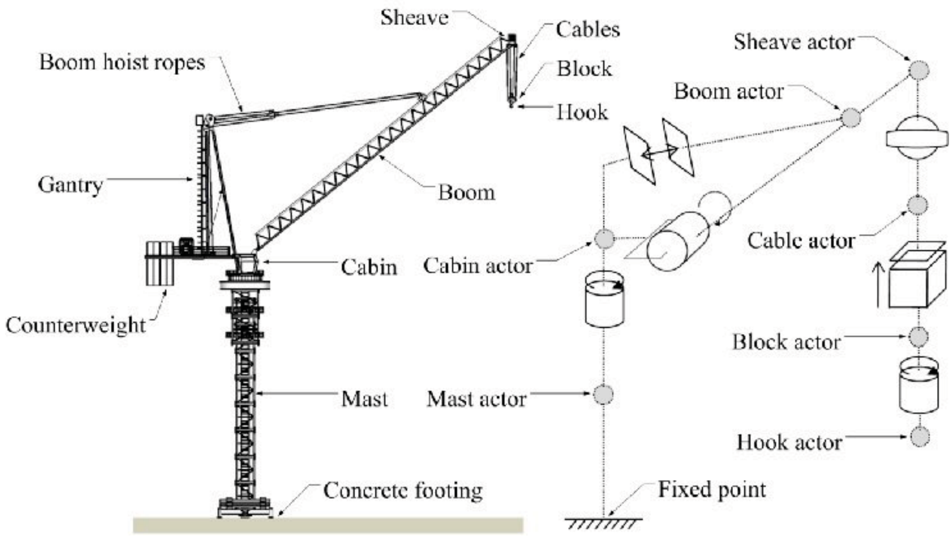


Fig. 7: A physical model of a virtual luffing jib crane.

5. Conclusion

This research proposed kinesthetic and stereoscopic vision methodology to reduce key differences between virtual and real environments for highly realistic and effective crane operation training. Kinesthetic and stereoscopic vision was developed using NVIDIA 3D Vision (a stereoscopic display toolkit) and a Kinect sensor (a body movement sensor). These provided binocular vision and feature a dynamic perspective depending on body motion. They allow trainees to intuitively examine spatial conditions in virtual scenarios. The proposed system utilized XNA and PhysX, a rendering engine and a physics engine, to visualize the virtual environment and simulate the physical behavior of cranes. The simulation results show that the use of kinesthetic and stereoscopic vision can help trainees to localize lifting objects more precisely. It can also help them to better comprehend the spatial conditions of operations by adjusting their head position to transform the visible zone in virtual scenarios. Future work will focus on user tests and verification of the proposed crane training system.

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CROWD MANAGEMENT SIMULATION IN STADIUMS

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ABSTRACT: *The interest in simulation in the field of crowd management is growing. Simulation models can show results about quality and safety of the facility, by evaluating normal operation and performing evacuation scenario's. Simulation of pedestrian flows on a mesoscopic level is very suitable for evaluating large-scale infrastructures with many simultaneously moving pedestrians. In the case of the Philips soccer stadium the benefit of using simulation for crowd management has proved its value.*

KEYWORDS: *Crowd Management Simulation, Crowd Control Simulation, Evacuation, Pedestrian simulation, Stadium Simulation, Stadium Safety*

1. Introduction

Since the nineties of the last century there has been a fast growing interest in under-standing and modelling pedestrian behaviour. In all kinds of environments the importance of analyzing and quantifying pedestrian flows is acknowledged. These range from urban design in public areas to effective product placement in a store to evacuation dynamics. Major reasons for this increased attention is that the quality of pedestrian flow and particularly the safety in pedestrian environments are more important than ever before.

Especially during emergency situations crowd management is an important aspect. Public facilities are getting bigger and bigger and still pedestrians have to be routed and evacuated through the building in a fast and efficient manner. Classical, qualitative manners of flow analysis are no longer sufficient. Therefore, simulation models are used to optimize proposed infrastructural designs and to test and improve the crowd management inside an existing or planned infrastructure.

Different approaches have been developed to model and simulate this pedestrian behaviour. In chapter 2 some general insight is created in the different models and approaches of pedestrian dynamics. In this article one of these approaches is discussed in detail, as it is the basis for the development of the stadium simulation model. Chapter 3 describes how this behaviour is captured in the crowd management simulation tool. Using this simulation tool the Philips soccer stadium in Eindhoven, the Netherlands, is modelled to analyze the pedestrian dynamics inside and outside this stadium. This case study is presented in chapter 4. Finally, in chapter 5 conclusions and recommendations for further research are summarized.

2. Pedestrian modeling and approaches

The research of pedestrian behaviour is mainly based on observations and empirical studies. The focus in this research lies on observing human behaviour and capturing pedestrian movements. In this way existing theories are extended and new theories are developed. The basic properties of pedestrian movements and its research are:

- Speed (m/s)
- Density (person/m²)
- Flow rate (persons/s)
- Throughput time (s)
- Inter-arrival time (s)

Fig. 1. Example of a crowded train station

In order to be able to model pedestrian movements the most important challenge is to capture the human behaviour, as result of the encountered circumstances. The most characteristic aspects of behaviour in pedestrian movements seem to be (HELBING et al. 2001):

- People select the quickest route to their destination and dislike taking alternative (slower) routes even if congestion arises on the initial route
- Each pedestrian has its own desired walking speed. This speed is dependent on both individual properties (e.g. age, gender, physical state, purpose of travel) as environmental properties (e.g. crowdedness, time, temperature)
- Pedestrians keep a certain distance to other pedestrians, walls and other obstacles. Dependant on the crowdedness in the area this distance between the pedestrian will differ.

Approaches to model pedestrian dynamics can be classified into three main levels (TAUBÖCK 2005):

- **Microscopic level:** In the microscopic approach, each pedestrian is represented individually. The individual entities have a unique behaviour. Also the mutual behaviour of pedestrians, like collision avoidance, is taken into account. The microscopic models can be described in two main approaches, either continuous (e.g. social force, HELBING et al. 1995) or discrete (e.g. cellular automata, BLUE et al. 2001).

- **Macroscopic level:** This approach describes the flow of pedestrians as a fluid through space. The main subject of this approach lies with the behaviour of the combined pedestrians in a group. The corresponding mathematical models are partial differential sometimes similar to fluid equations (e.g. BAUER et al. 2007)
- **Mesoscopic level:** In a mesoscopic approach the individuality of each particle is maintained. During each time step, particles are aggregated to field quantities such as density, the velocities are computed from these densities, and then each individual particle is moved according to these macroscopic velocities (TAUBOCK et al. 2005).

3. Simulation

The simulation application that forms the basis for this study uses a mesoscopic approach and is developed with the discrete event simulation software Enterprise Dynamics. The basic concept of the application is the controlled movement of individual entities (pedestrians) between locations over a node network.

The position of the nodes in this network is determined by the infrastructure (e.g. train station, airport, and stadium) that is analyzed. In this infrastructure all relevant areas with their corresponding sizes are created by the user. Dependant to the infrastructure, the areas are connected by placing nodes in the area and connect them to each other. These nodes can represent either network intersections, passages or links to processes (see figure 2). Stairs and escalators are special types of nodes with adjusted speeds and capacities.

The application's purpose is to analyse the "performance" of a functional infrastructure, for example a train station, airport, exhibition hall or stadium. Based on the purpose and destination of the pedestrian it will have (multiple) sequential destinations inside the infrastructure. A traveller will for example go to a ticket machine first and then to the train platform. Based on the defined destination sequence of the pedestrian it will follow the shortest and or fastest route to fulfil its purpose within the infrastructure. At every node in the network (graph) the pedestrian passes, the next node in the route is determined by the Dijkstra Algorithm (DIJKSTRA 1959). This algorithm calculates the shortest routes over nodes in a graph network.

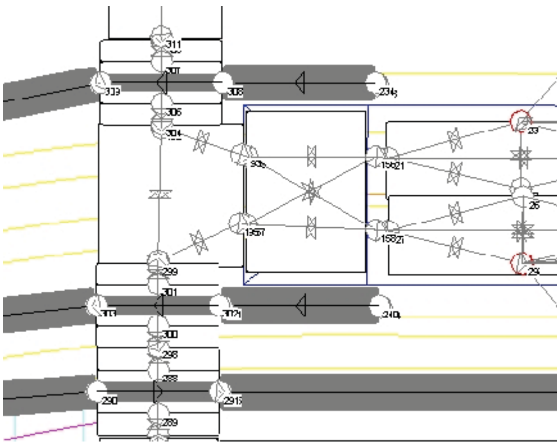

Fig. 2: Areas and node network

Dependant to the properties (e.g. age, purpose, gender) of the pedestrian, it will have a desired walking *speed*. Based on the density in the area and the desired walking speed the pedestrian will have a certain walking speed, while travelling from one node to the next. Each time the pedestrian enters a node its walking speed is adapted according to the density of the area the pedestrian is in.

The degree of increase or decrease of the travel speed is a result of the speed-density relation, researched by FRUIN (1971). In figure 3 a graph is presented that shows the relation between desired walking speed and density.

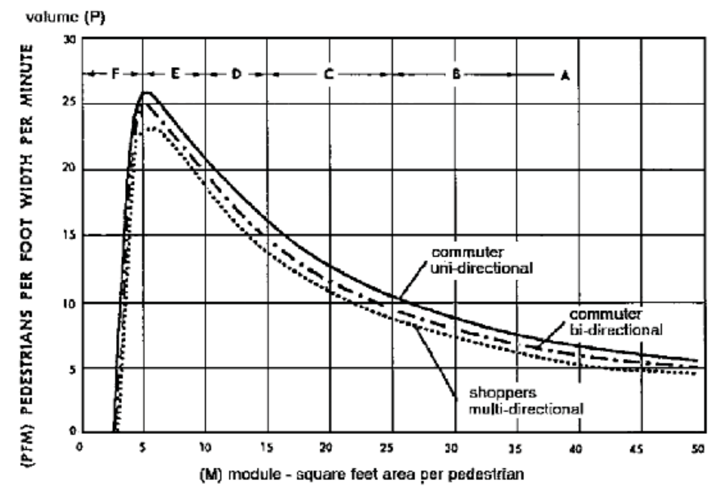

Fig. 3. Speed vs. Density

Apart from the network and the walking behaviour also functional processes (e.g. ticket sales desks, ID check gates, shops) are taken into account. These processes are modelled as "servers" with corresponding properties (e.g. capacities, cycle times). As a result of the finite capacity, the cycle times and the distributed inter-arrival time of the pedestrians, queuing and congestion can arise.

Event-based simulation tools are very suitable for the mesoscopic simulation approach. Every time a pedestrian enters a process or node, an event is created for determining the current state (e.g. density) of the area. Based on this state, the pedestrian will act in accordance with certain pre-defined behaviour. This behaviour is extracted from microscopic research of pedestrian flows. For this study the discrete event simulation software Enterprise Dynamics has been applied.

Microscopic models often use forms of continues simulation. In these simulations the surrounding of a pedestrian (also called agent in this manner) is monitored continuously and the behaviour of the pedestrian is adapted instantly. Microscopic research is often used to validate a model that represents the exact behaviour of pedestrians in small areas. Due to the continuous monitoring of all the pedestrians in the model the required computer processor capacity of these models is very high.

Therefore large-scale microscopic simulation models are rare. Since the discussed mesoscopic simulation application is very well capable of dealing with large numbers of pedestrians and large scale routing networks, it is very suitable for modelling large infrastructures such as train stations, airports and soccer stadiums. Several simulation models have already reached a simultaneous content of over 70,000 pedestrians.

In the next chapter a practical application of the large scale pedestrian simulation tool is discussed.

4. Stadium Crowd Simulation

The case study concerns the pedestrian dynamics in and around the Philips soccer stadium, home of the soccer team PSV Eindhoven in the Netherlands.

The goal of the stadium case was to develop a customized simulation model of this soccer stadium with over 35,000 seats. With this model, the security managers, who are responsible for safety and visitor protocols, must be able to perform:

- Analysis of pedestrian crowd flows, both inside and outside the stadium,
- Analysis on changing infrastructure and protocols,
- Development and analysis of evacuation scenarios, and
- Capacity planning of processes and personnel.

The security managers are the end-users of the application and must be able to modify settings and perform their analysis autonomous. Therefore the constraints for the application and its model were not just functionality, but also ease of use and adjustability.

Important performance indicators in this application are the densities in the different areas of the stadium and the waiting times at the different processes (e.g. entrance gates, ticket sales etc.) before, during and after a match and off course the evacuation time of the visitors.

Fig. 4: Philips Stadium, Eindhoven

The main aspects that influence this performance in the stadium are:

- the lay-out of the stadium and its surroundings,
- the arrival intensities of the visitors,
- visitor properties,
- the entrance & exit gate distribution, and
- the use of processes (facilities).

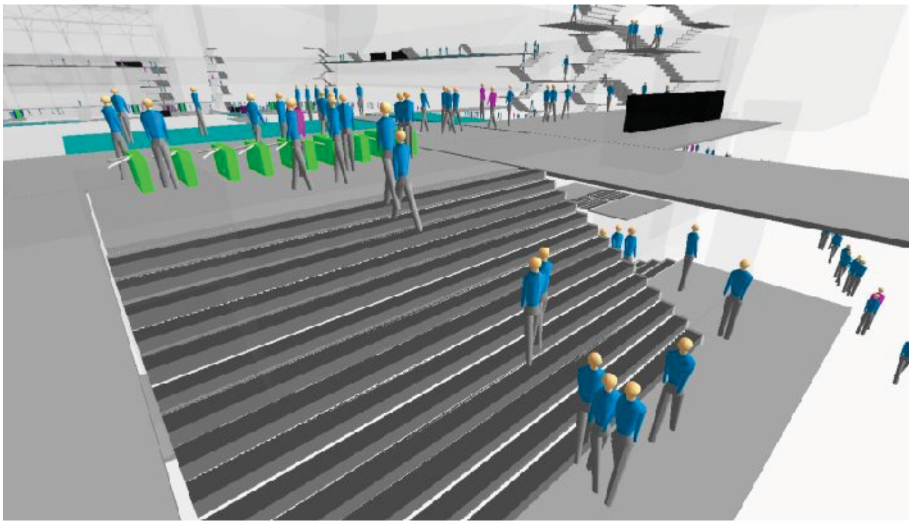

Fig. 5: 3D Visualization simulation model

The model is constructed exactly on scale by using a CAD drawing of the infrastructure with all relevant floors taken into account and is visualized in both 2D as 3D. The model structure is created by defining all relevant walking areas and intersections (nodes). Within this node network links to processes are indicate, so that the pedestrians can go to the several (sub)destinations. In figure 5 a 3D screenshot of a stadium staircase area is presented.

4.1 Functionality

The following functionality was implemented in the routing management of the pedestrians both to simulate a truthful model and to allow the security team to evaluate alternative scenario's.

- **Arrival:** Visitors enter according to a Poisson distribution defined per time interval. In this way the effect of changing the intensity per time window before the game can be analyzed.
- **Entrance allocation:** Due to the **internal** infrastructure of the stadium on a general level the stadium is divided into four main sections (North, South, East, and West). In these sections several entrances (with turnstiles) and tribune areas are located. In the application the user is able to allocate turnstile entrances based on the tribune of destination and in that way to select an optimal allocation strategy for assigning pedestrians to one or more entrances.
- **Facility usage:** Based on user **settings** each pedestrian is assigned a random combination of facility properties. Examples are visiting a bar before the game or visiting the toilet during the break. Owing to these properties and the game status (before the match, during break or at the end) pedestrians walk to the local sub destination which represents the facility. After the process time and potentially a waiting time, the pedestrian can walk to a next process and finally to its end destination, the tribune seat (during start-up and break) or the exit (at game end). By changing these facility usage properties the model user is able to analyze the effects of changing facility behaviour of the pedestrian on stadium performance.
- **Evacuation:** At any moment **during** the simulation run the user is able to start up an evacuation. At that point each visitor will receive an end destination node which is the closest available (emergency) exit. Also the desired walking speed of the pedestrian will be adapted according to a pre-defined distribution of emergency walking speeds. In order to evaluate a wide range of emergency situations, the user is able to close different sections or exits during an evacuation (e.g. to

simulate a fire) and thus analyze the effect of this situation on the infrastructure usage and the selected protocols.

4.2 Performance

To analyze the "performance" – the quality and safety - of the selected crowd management decisions, several performance indicators are monitored within the simulation. In this case the most important indicators are area densities, travel times (including evacuation times) and waiting times.

- **Densities:** The density is stated as the m² per person. This density shows the level of comfort in this area. Based on the "level of service" concept (FRUIN 1971) six levels of comfort are stated in the output. This density is monitored per defined area per time interval. In this way the user is able to discover bottlenecks and their duration in the proposed pedestrian flow.
- **Travel and evacuation times:** The travel times between origin and final destination is monitored. This is especially important for the evacuation scenario. Since there are governmental guidelines for the maximum time needed to travel to a safe area, the user is able to test the available or proposed evacuation and emergency protocols. In figure 6 an example of the evacuation time distribution of a certain tribune is shown.
- **Waiting times:** The waiting times are monitored at both the entrance gates as the several facilities in the stadium in order to determine the "service" level of these processes. Results are presented in histogram classes for comparison with standards as dictated by the authorities.

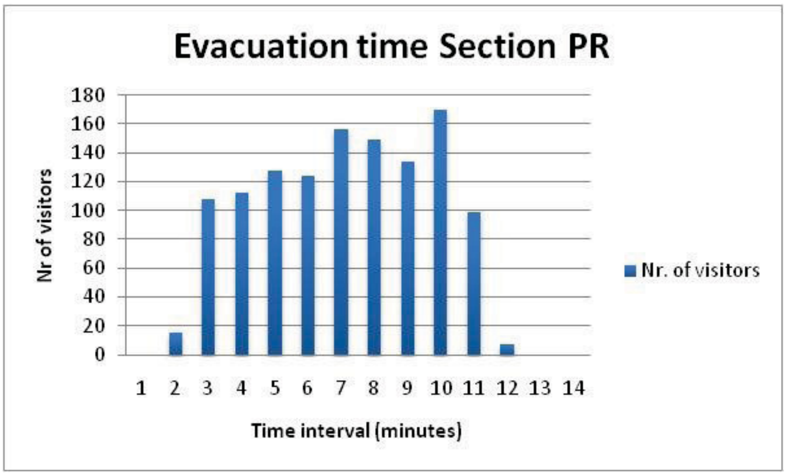

Fig. 6: Output Example; Section evacuation duration

This business case discusses the development of an application that is used by external users for operational analysis. They make crowd management decisions based on the results of experiments as expressed in these performance indicators.

5. Final remarks

The benefit of simulation for the analysis of pedestrian flow was evident in this project. The user was able to perform scenarios which were never evaluated before, simply because it was practically to complex to attempt these scenarios in reality.

In general, it can be stated that due to the physical scale of the infrastructures in combination with the complexity and (financial) consequences of testing in reality, the developed simulation tool is very suitable to deal with these logistical pedestrian questions. The security managers of the Philips stadium use the model on operational basis to test and evaluate scenario's.

In relation to the majority of other simulators the main difference is that a mesoscopic approach is used instead of a macroscopic or microscopic approach. The application using this approach enables large scale pedestrian systems with huge numbers of moving entities (e.g. 70.000 visitors), while treating them as individuals with personal characteristics.

Regarding the mesoscopic approach some recommendations for further development and extensions of the model are stated.

- **Route selection:** In the current selection algorithm the shortest route is selected, disregarding the crowdedness on this route. In the current application the Dijkstra Algorithm is used to calculate the minimum distances between al network nodes. The cost of a route in this manner is only dependant on the distance. Suggested is to develop for example a dynamic Dijkstra algorithm that can be executed during a simulation run. Using this dynamic algorithm a pedestrian can select the optimal route to his destination based on a cost function. This cost calculation is then a function of variables such as distance, pedestrian preferences and crowdedness on the route.
- **Evacuation:** Although the application allows several variants, in the current evacuation scenario the pedestrians in the model will select the shortest emergency exit as destination. In reality this selection of an exit is very complex. From research (SOOMEREN 2007) it is concluded that the selection of an emergency exit is dependent on many factors such as pedestrian properties, crowdedness, signing, familiarity with the building and the used entrance. It is proposed to develop a more complex selection algorithm that can take all these factors into account.

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A SIMPLIFIED METHOD TO RENDER PRODUCTION AND RESOURCE UTILIZATION ANALYSES FROM A 3D-MODEL

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ABSTRACT: *Waste is evident in the construction industry. Due to the dynamic nature of on-site logistics, resources, equipment and machines related to time and space, construction processes are difficult to fully grasp, communicate and evaluate manually. Hence better tools to manage and analyze these processes are required.*
This paper presents a simple Project Information Database (PID), previously developed by the authors, in which object data is complemented with definitions. By means of these definitions and the object data, the PID creates linked activities and resource requirements in a semiautomatic manner. The system provides control of both material-flow and resources needed in a construction project, hence making production analyses possible. By means of a simulation tool, planned production can be simulated without any extra effort since activities and model objects are linked through the PID. An example of analyses gained is the required capacity of cranes: which areas does a crane have to reach, what is the weight capacity and how many lifts per day? If the required resources are specified based on the analyses and added as objects into a parametric 3D-model, these are automatically linked to activities, once their object data has been transferred to the PID. The digital linkage of planned production data makes it easy to compare production methods, resource and site-layout alternatives or to update parts of data and view their consequences in both virtual and non virtual analyses. Particularly, analyses of machinery utilization rates can provide a sounder allocation with as little overcapacity as possible.

KEYWORDS: *Production Analyses, CM, BIM, 3D-Model, VP, Waste, Resource Utilization.*

1. Introduction

For many Swedish construction projects, the design phase is partly ongoing parallel to the project planning at the same time as parts of the production have already started (Jongeling 2008). Not surprisingly the construction industry is resource inefficient and has not progressed since 1964 in regard to labor productivity when other industries have improved their resource efficiency (Kymmel, 2008; Eastman, 2008). Hence waste is evident in the construction industry (Josephson & Saukkoriipi, 2007). Waste is defined here as activities that can be eliminated without affecting the outcome. In the study by Josephson and Saukkoriipi (2007) as much as 30-35% of a construction project's total cost is pure waste. Focusing on where in a project this waste is located, it becomes clear that the on-site production carries the larger portion. Two thirds of the project's total waste could be related to activities performed and resources used on-site. These include transportation, machinery, operational costs and on-site labor. A potential to lower the cost, increase the profit and deliver a better product by optimizing these processes is hereby evident.

These production resources and processes can be reviewed in a wider view of logistics. Commonly logistics is defined as: "*The process of planning, implementing, and controlling procedures for the efficient and effective transportation and storage of goods including services, and related information from the point of origin to the point of consumption...*" (Council of Supply Chain Management Professionals, 2010), by expanding this definition to also include surroundings and preparatory works related to the material being moved, stored or incorporated, the wider view is gained. Also, surrounding and preparatory work concerning the material varies depending on the choice of production method. The material concrete can be used as an example; if concrete is cast in place, forms need to be mobilized, assembled and removed for each predefined section and it may or may not involve the use of a crane. This is in contrast to the use of prefabricated elements where there is next to no need for preparatory work, but where a lifting device is more or less mandatory. Although the cast-in-place needs more time for completion and it can allocate entire floor areas when shores are used, prefabrication requires more additional unloading space and heavier lifting equipment since the elements are usually quite bulky.

In this paper, on-site production and resources and their corresponding waste are analyzed through this wider view of on-site logistics which is more than the flow of material itself. This wider view includes the choice of production method and primary resources. Primary resources are those objects in direct contact with the material such as concrete trucks, concrete pumps, mobile and stationary cranes, people, hand held tools, wheel barrels etc.

As the dynamic nature of on-site logistics, resources, equipment and machines related to time as well as space (H.J. Wang et al, 2004) makes construction processes difficult to fully grasp, communicate and evaluate manually, better tools to manage and analyze these processes are required.

During the recent decade there has been a tendency in the construction industry towards adopting 3D-models. A keen observation by Smith and Tardif (2009) highlight that the geometrical information in a 3D-model only constitutes a very small fragment of useful model data which has the ability to be used for later purposes. If a model possesses the ability to include object specific parameters such as material type, density and unique identifier, but also the ability to communicate these attributes, it is defined as parametric (Eastman et al., 2008). This digitally stored object data can swiftly, by computerized means, be used for other purposes than drawings. Different ideas for applications where this data could be used are frequently debated. Nevertheless, up to now, only a few detailed examples for the purpose of analyzing the production have been presented.

By implementing a simple Project Information Database (PID) previously developed by the authors (Bostrom T. and Sjödin E., 2011), object data is complemented with definitions by means of which the PID create linked activities and resource requirements in a semiautomatic manner. The system provides control of both material-flow and resources needed in a construction project, hence production analyses are made possible. By means of a simulation tool, planned production can be simulated without any extra effort since activities and model objects are linked through the PID. If the required resources are added as objects into a parametric 3D-model, these are automatically linked to activities, once their object data has been transferred to the PID, and can thus be incorporated the same way into the simulation. The digital linkage of planned production data makes it easy to compare competing production methods, resource and site-layout alternatives or to update parts of data and view their consequences in both virtual and non virtual analyses. Particularly, analyses of machinery utilization rates can provide a sounder allocation with as little over capacity as possible.

Platforms with a similar approach have been and are currently being developed. Examples are the German research project Mefisto (Scherer et al., 2010) and the Chinese platform called 4D Management for Construction Planning and Resource Utilization with the acronym 4D-MCPRU (H.J. Wang et al., 2004). This paper does not claim to describe a more comprehensive system, but rather how a simple system without extensive funding can and has been distributed. It also describes the processes that are involved in the visualization of the on-site logistic and resource analyses. Also in contrast to Wang et al.'s research, this paper's focus is to use the strength of existing software, and complement them with the missing parts by distributing structured information.

This paper's aim is to describe the method and processes used to create in depth production and resource utilization analyses based on the data collected from parametric 3D-models by means of the PID. It is also about describing the analyses that were gained and their purpose, as well as giving indications of other possible analyses that can be gained by using the system provided. Thus the focus in this paper is not on the transfer of data nor on the commercial software used for modeling, scheduling or simulating.

2. Results & Analysis

This chapter will explain the procedure when generating production analyses for the scope in the applied project and hence the function of the PID. Each step in the process (① - ⑨, Fig. 1) is explained in the sub-chapters.

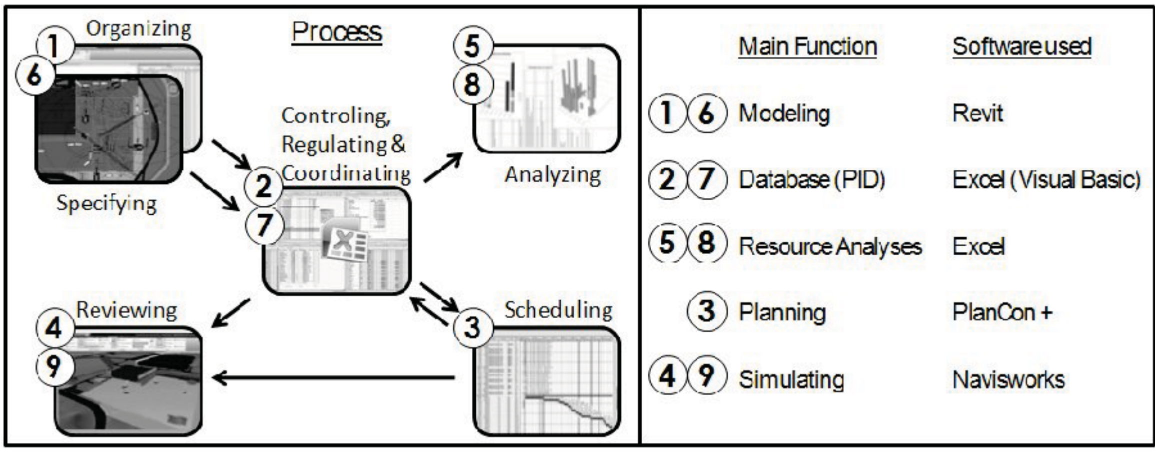

Fig. 1: The applied process for analyzing the production and each tool´s main function and software used.

The Project Information Database was programmed in Visual Basic, Excel, in which ideas of how to complement and structure building data to render analyses, were continuously tested. A process model for how to utilize the newly developed system was also designed and tested. All tests were performed based on the 3D-models created for the live project of a combined public bath and ice rink facility. The scope of production works and material selected were limited to concrete, both prefabricated element and cast in place, due to the bulky nature of equipment used to work with these objects and materials on site.

2.1 Preparations and storing of object data in the 3D-model ①

Object parameters were imported into the PID via the 3D-modeling software's schedule. Object specific parameters chosen to be stored in the schedule (Fig. 2) were a unique identifier, family and type, location tag, level, zone within the specified location, simulation number, area, volume, length and material type. All scheduled parameters were organized in a specific order to lower the amount of required programming to automatically structure the data in the PID. Schedules were stored in a specific folder linked to the PID.

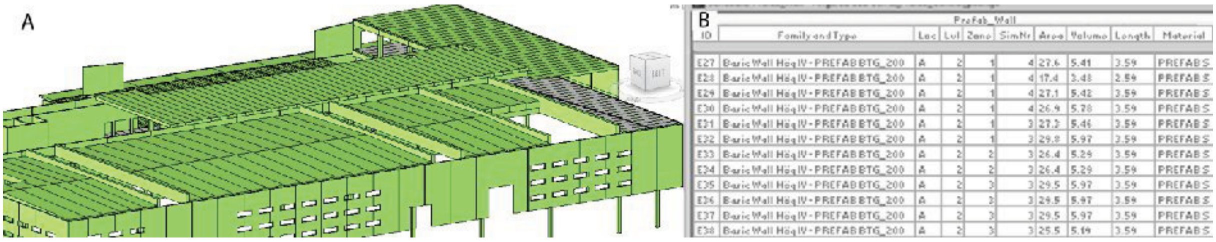

Fig. 2: Stored object parameters in a schedule [B] from the prefabricated concrete model [A].

The family and type label was used in the process both as an object description and as a tag which allows the system to aggregate objects in unique object-groups. Thus labels had to be suitable for automated structuring and distinguishable among thousands of objects. Hence some labels had to be changed for two reasons: Firstly, due to inconsistent labeling by the designers e.g. different labels for the same object-type; secondly, a few objects had to be differentiated in terms of their inherent function. The Swedish BSAB coding system for construction components and production result were added as a parameter intended for this purpose, though it failed because it was too imprecise to distinguish elements with explicit purposes i.e. concrete walls and slabs for the ice pit, the grand stand etc. A recommendation concerning this issue is given in the Conclusions and recommendations.

Further on all prefabricated wall elements had to be divided into their actual sizes so that the data and visual simulation would be relevant and precise. Also concrete slabs were divided into plan able sizes.

2.2 Adding and structuring data in the Project Information Database ②

Object data from the models were incorporated automatically into the PID via the stored schedules. Once an update to the model had been performed, updated schedules were stored and hence added to the PID. To make these modeled updates traceable, the PID was programmed to recognize changes. New objects were marked green, changed objects were marked yellow and deleted objects were marked red; in addition, a revision date shows when the change was performed.

To generate production analyses based on approximately 1300 objects, additional data had to be attached to the imported object parameters. The purpose of this additional data is mainly to generate production analyses; though in order retain the required detail-level without entailing unreasonable manual scheduling, activity and object specific definitions are also established and attached. This helps the PID to automatically organize and aggregate data into planable activities. In the scope of the applied project, 40 activities requiring manual scheduling were generated by the PID, which corresponded to the amount of manually generated activities by traditional means in the same project.

The following sub-chapters describe: The additionally attached data and the established activity and object specific definitions through which the PID generated about 3000 activities which individually were linked to a specific object in the model; and how activities were internally pre-linked based on these definitions and aggregated into groups in different hierarchies.

2.2.1 Defining material density

By reviewing the imported material type parameter, a density was added through which the PID calculated each object's specific weight. There are two reasons for this rather simple procedure being performed outside the design software/3D-model: first of all, as of today, it is too complicated to establish the weight based on the objects withholding materials density within Revit; secondly the specific design of some objects may be irrelevant for the designer as long as they meet the specified demands. The prefabricated concrete is such an example. 1300 unique objects from the structural framework models corresponded to 13 unique material types, automatically presented in the PID.

2.2.2 Defining required production activities and resources

Activities and required resources were defined in the PID. Definitions were based upon previous experience and stored production rate data. In the scope of the applied project, 33 unique activities were defined.

1	Activity label	h/unit	unit	machines	Units/ Lift or delivery		Activity-Family	Code	Nr
13	BTG sulor pump	0,378	m3 (del)	B	5,5	m3 (del)	BTG sulor pump	BTG	6
14	BTG trappor	1,56	m3 (hel)	B	5,5	m3 (hel)	BTG trappor	BTG	6
15	BTG vägg pump	0,378	m3 (del)	B	5,5	m3 (del)	BTG vägg pump	BTG	6
16	PREFAB HD/f 200	0,2	st	K, MK	1	st	Prefab	PRE	6
17	PREFAB HD/f 380	0,27	st	MK	1	st	Prefab	PRE	6
18	PREFAB höga väggar	1	st	MK	1	st	Prefab	PRE	6
19	PREFAB låga väggar	0,57	st	MK	1	st	Prefab	PRE	6

Fig. 3: Unique activities defined by production rate, machine usage, personnel requirement and activity family.

As shown in Fig. 3 all activities were assigned a planned production rate in h/unit which results in a period of time required for the activity once combined with the object data. Also activities machine requirement (B = concrete truck, K = Crane, MK = Mobile crane), machine-capacity (Units/Lift or delivery), and the number of personnel were added. Later on in the process, these definitions will provide analyses regarding need for crane-capacity, concrete delivery and personnel-requirements in time. Additionally this step also includes defining the activity family. An activity family includes different activities of the same kind, examples of activity families are prefabricated concrete or reinforcement.

2.2.3 Defining object-activity connections

Activities were defined to construct objects in a list where all unique objects were automatically presented. The scope of the applied project contained 108 unique objects. Objects can be defined to include several activities i.e. a concrete wall comprises the activities of form-work, reinforcement and poring of concrete (Fig. 4).

Object	Object Family	Mtrl	t [m]	Activity 1	Link	Bffr [d]	Mtrl	t [m]	Activity 2	Link	Bffr [d]	Mtrl	t [m]	Activity 3
Balk Stål VKR: Strävor K200x200x6.3	Stål strävor			STÅL pelare/balk										
Basic Roof: TRP_110 ISO_50 ISO_200 ISO_50	ISO tak		0,1	TRP	F-S				ISO tre lager					
Basic Wall: Bad - Akt. bad BTG_250	Bad akttrappa			FORM trappa	F-S	1		0,3	ARMering 18,20 m3	F-S				BTG trappor
Basic Wall: Bad BTGVT_250	Bassängvägg			FORM vägg	F-S	1		0,3	ARMering 18,20 m2	F-S			0,3	BTG vägg pump
Basic Wall: Bad relax - BTGVT_250	Bad relax			FORM vägg	F-S	1		0,3	ARMering 18,20 m2	F-S			0,3	BTG vägg pump

Fig. 4: Unique objects from the applied project presented in a list in the PID.

The detail level is defined by the user i.e. it is possible to break down an object into as many activities as preferred (as long as the activity has been pre-defined). If an object comprises several activities, internal activity links are established, i.e. Start-Start, Finish-Start and if any buffer time (Bffr) is required in the specified link. An object-family was also added to the objects in this step to render automated organizing of information in later processes. An object-family collects objects which, due to type and/or location, should be created during the same time sequence.

2.2.4 Defining desired location-based production sequence

To further grade activities in a sequential order, definitions for a desired location-based production sequence was made in the PID. This definition is based on the objects location tag, level and zone; where zone is a subordinate to the level which in turn is a subordinate to the location. Thus the defined sequence for locations can be: firstly Location A, secondly Location B, thirdly Location C etc. and the sequence for levels within a specific location can be: firstly level 1, secondly level 2 etc. and so forth for zones. Definitions can be applied in general terms or if desired, specified differently for different activity families.

2.2.5 How activities are linked, structured and aggregated into groups

Through the definition procedures performed, the PID generated about 3000 activities which individually were linked to a specific object out of the existing 1300 in the models. To plan 3000 activities in time would be a tedious process, therefore the PID automatically links and aggregate activities into groups in different hierarchies before they are transferred to a planning software. The automated aggregations and linkage are based on object-family, activity-family, location, level, zone, activities comprised in a unique object and their individually defined links. There are three hierarchies (Hrchy) of aggregating activities which in the next paragraphs are called A, B and C. Hrchy A activities aggregates one or several Hrchy B activities, whereas Hrchy B activities aggregates one or several Hrchy C activities (Fig. 5). Basic activities are aggregated in the Hrchy C activities.

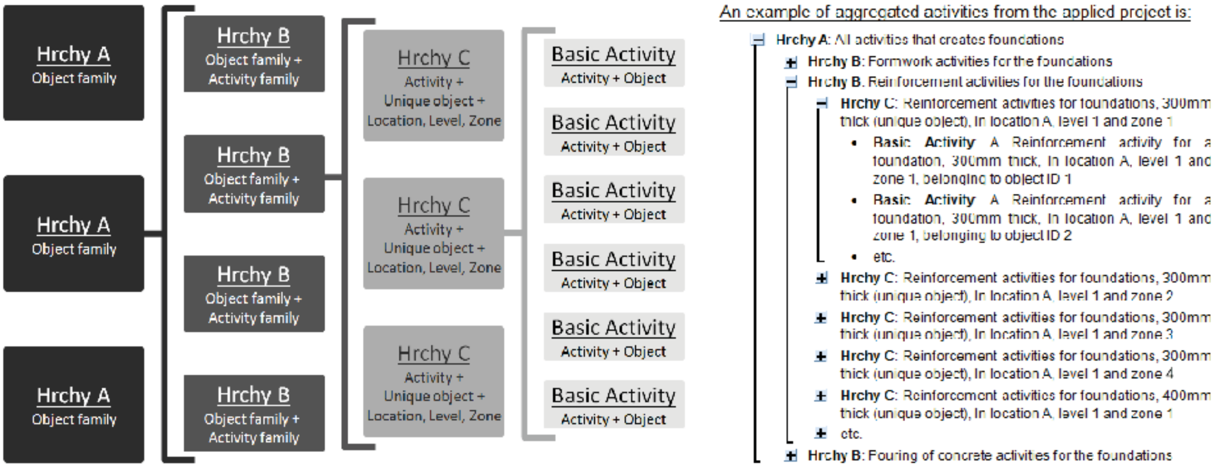

Fig. 5: How activities are aggregated into hierarchies (left) with an example from the applied project (right)

Hrchy A activities are defined by the object-families; these are organized but not linked according to a user concluded production sequence. An object-family is a number of unique objects, which due to their type and/or location should be created during the same time-sequence (Fig. 4).

Hrchy B activities are composed by the combination of an activity-family and an object-family. An activity-family is activities of the same kind (Fig. 3), which means that Hrchy B activities aggregates activities of the same kind that belong to objects which should be created during the same time-sequence. An example of such a group in the applied project is reinforcement-activities for the pool floor concrete slab. Hrchy B activities is foremost a container to make activities easy to survey and re-plan manually in a planning software. A Hrchy B activity do not hold any link, it gets its place in time-space through its aggregated activities' links (Fig. 6).

A ***Hrchy C activity*** is an activity that creates a unique object in a specific location, level and zone (Fig. 5). The last listed Hrchy C activity that belongs to the first Hrchy B activity is linked to first listed Hrchy C activity contained in the second Hrchy B activity (Fig. 6). These links are created according to the user specified definition of activities belonging to a unique object (Fig. 4) for example finish-start with a specified buffer-time.

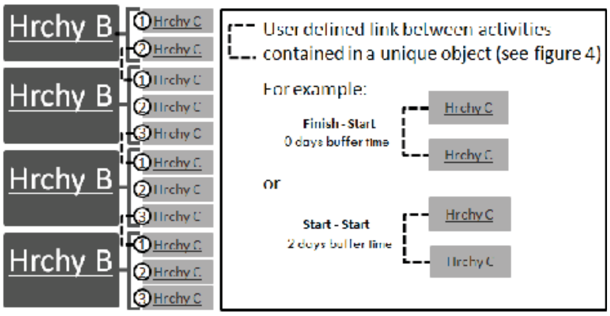

Fig. 6: Linkage between activities belonging to separate activity-families that cooperatively create an object.

Within the Hrchy B activities, the Hrchy C activities are arranged according to their location, level and zone based on the user defined preferences and linked with finish-start (Fig. 7A).

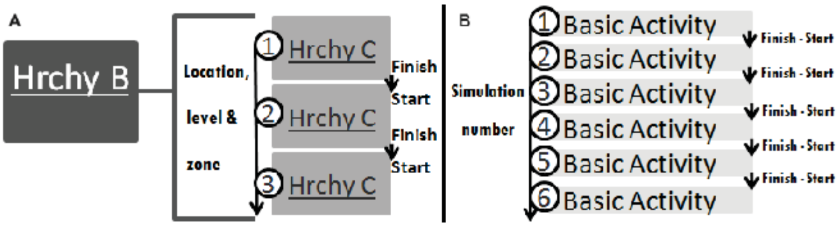

Fig. 7: Linkage of Hierarchy C activities contained in a Hierarchy B [A]; and linkage of basic activities [B]

Lastly one basic activity which corresponds to one modeled object is arranged in relation to other basic activities belonging to identical object types in a specific location, level and zone according to their simulation number and linked with finish-start (Fig. 7B). This number has been typed into the parametric 3D-model manually for each object to gain an orderly simulation. An automated procedure is suggested in the Future outlook chapter.

2.3 Scheduling activities in the planning software ③

Within the planning software, the unlinked hierarchy A activities were scheduled and linked. The aggregated lower activity hierarchies were used as references to find the right overlap for instance when a specific space is free to populate by a subsequent activity. Also the predefined personnel requirements were adjusted to make the activity time-periods fit into the projects time-frame or to synchronize parallel activities visible in a Gant-Chart. If desired, other resources could also be edited in this step. A program which had a flow line view was chosen since an idea was to review and identify space issues in the schedule. Unfortunately it failed since activity locations were not connectable or transferable to locations defined in the planning software. Also it was not possible to turn on or off hierarchies in the flow line view as it was in the Gant view, thus the view got too hazy.

Due to the large amount of information handled, the planning software tended to occasionally work slowly or render fatal errors. After scheduling, data should be transferred back to the PID, to support other analyses.

2.4 Simulating object erecting activities ④

As shown in the work process picture (Fig. 1) step ④, a visual simulation can be generated of the planned construction element erection once steps ①②③ have been performed. This is done by combining the schedule and 3D-model graphics in a simulation software. All 3000 activities and 1300 objects within the scope of the applied project were automatically connected through the unique object identifier by applying a rule in the simulation software. By programming the PID to also add simulation specific data, visual effects were added by default e.g. making an object red for reinforcement works, yellow for formwork, green for pouring of concrete and original model-colored for finished etc. Thus the tedious process of setting up these rules, for each object, every time a simulation is performed is avoided.

Production issues identified in this step were activities being performed closely to simultaneously and activities performed in an unpractical order. An example is an activity that ought to be moved since the object it is erecting renders space issues for a subsequent or parallel activity. If issues are identified, the project plan is updated accordingly. This process can be repeated until satisfactory results are gained.

2.5 Resource capacity analyses ⑤

All data concerning resource requirements and when in time these resources are needed are stored in the PID once steps ①②③ have been performed. Hence charts were easily generated by default, which showed how much capacity that was required during different parts of the project. Fig. 8 shows the crane capacity requirements, which are based on the information established for activities in the PID. For example, how many meters of wall that are the result of a number of crane lifts of formwork for different wall types (Fig. 3). Fig. 8 Chart A shows how many crane lifts that are required for prefabricated concrete and concrete works. Looking at a specific week more closely, as in chart B, you can see that two operating cranes are required to get enough lifting hours, this might be the case anyway when studying locations required to be reached, in chart C. Chart D indicates weeks that require stronger cranes due to heavy lifting.

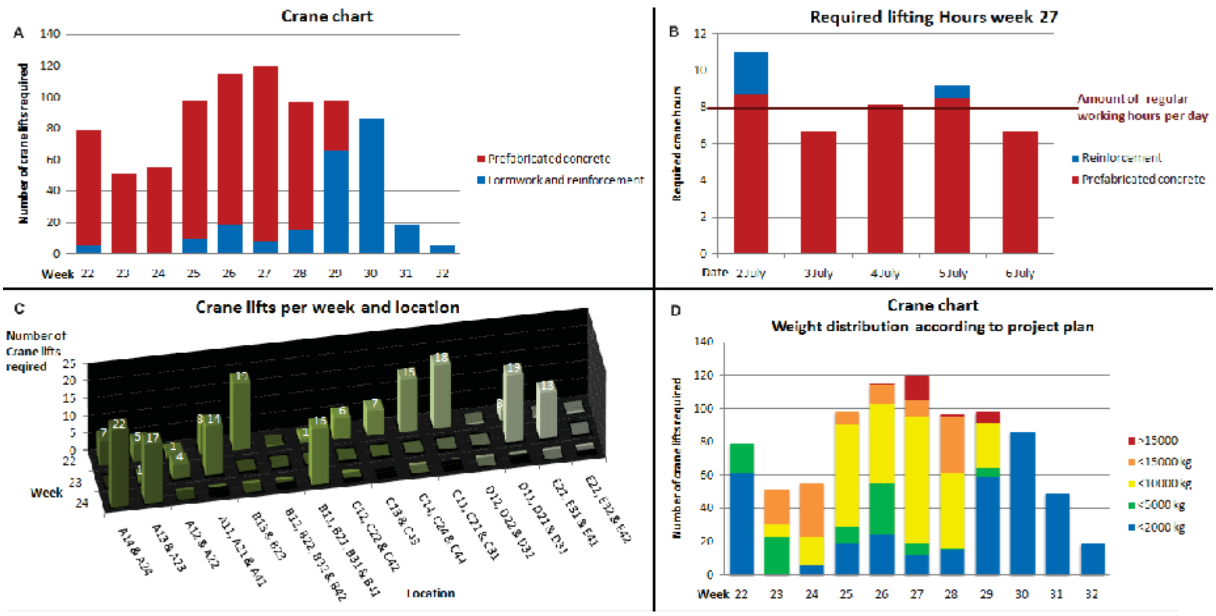

Fig. 8: Crane capacity requirements presented in four different charts

Other analyses were also established in this step, for instance as shown in Fig. 9, the usage of barrack space for manual labor and the amount of concrete deliveries. Chart A visualizes the required number of barracks for manual labor between weeks 22-32 and describes how well they are utilized if the highest requirement is governing. Chart B shows number of concrete truck deliveries required per day week 22 and how well their mixer space is utilized. Both these charts give an indication of how to distribute the site (required space for barracks and road capacity).

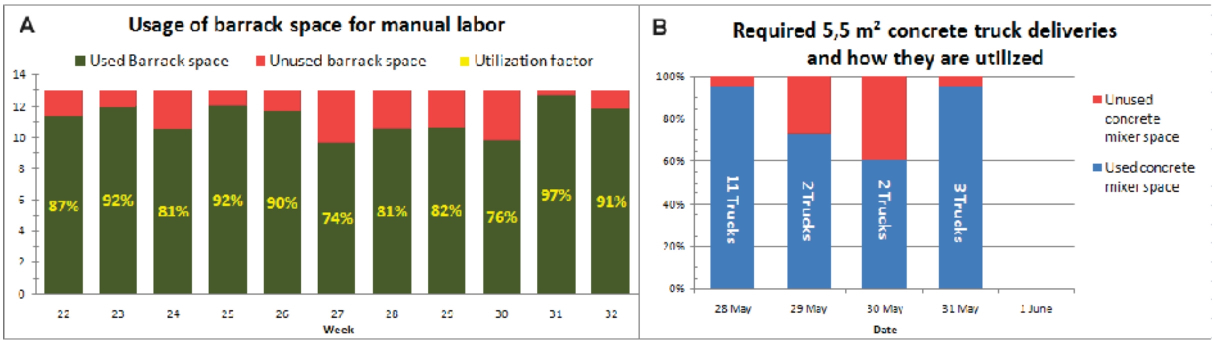

Fig. 9: Barrack space [A] and concrete truck delivery [B] analyses

A variety of analyses can be generated based on the resource data added into the PID. The requirement analyses serve as support for the project plan and for specifying on-site machinery, equipment and site-layout.

2.6 Specifying on-site machinery, equipment and site-layout ⑥⑦

Large machines and equipment were placed into context to gain knowledge about space issues, how the site should be distributed and suitable resources. The context was a 3D-model containing surrounding buildings, environment and linked in construction models. Accurately modeled cranes, mobile cranes, concrete trucks, boom pumps, barracks, fencing, waste- and storage containers were added along with temporary roads.

Some aspects can be reviewed by looking at the planned site-layout in Fig. 10. For instance, it was identified that there was too little space at a corner of the building [A] along the temporary road, for construction logistics to not interfere with the pedestrian road and thus a temporary pedestrian road was suggested [F]. Access routes were established [B], space for barracks [C] and waste containers [D] was suggested, and the length of fencing [E] collected as it was placed into the model.

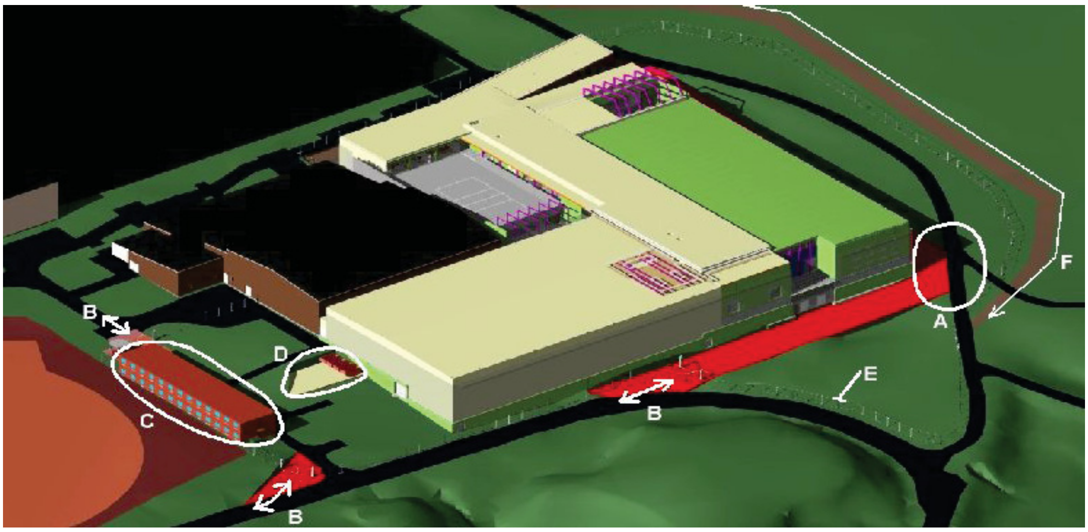

Fig. 10: Suggested site-layout with highlighted aspects

Fig. 11 shows machinery being positioned into the 3D-model. A maximum weight capacity chart for locations [A], was used as support when placing the cranes [B]. The modeled circles around the cranes describe the weight capacity in radiuses from the crane center. Yellow objects are mobile cranes, green and blue are stationary cranes and the white objects are concrete trucks and boom pumps which were placed into their unloading positions.

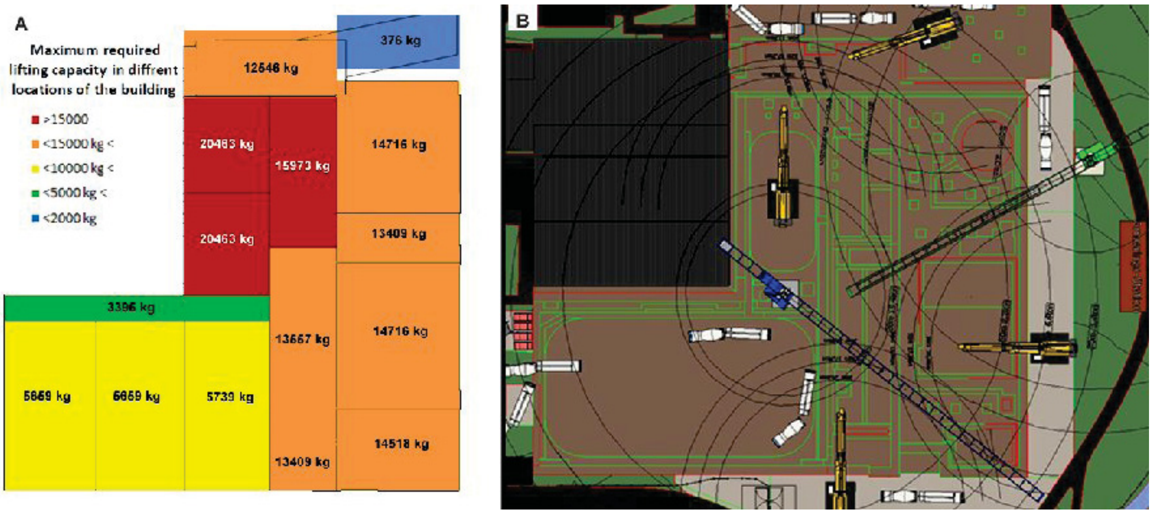

Fig. 11: Positioning of concrete deliveries and cranes [B] supported by a weight capacity requirement chart [A].

When placing a certain crane configuration it was possible to see: If the crane had enough weight capacity, if the crane reached the required locations, if the height of the crane configuration was enough to lift the element/material above the already erected building elements, if there was enough space for trailers carrying prefabricated concrete on a reachable distance from the crane, and also if cranes placed inside the building interfered with activities or building elements.

Another interesting aspect appeared as a few wall elements entailed either that one of the stationary cranes (blue in Fig. 11) had to be moved earlier than planned, or a remarkable enlargement of either the stationary or mobile cranes was required. Hence it would be less resource consuming to reduce the width of these elements, which was a possible option since they had not yet been prefabricated.

Simultaneously as the on-site machinery was specified for the applied project, the resource requirement notation for activities in the PID were altered for most of the prefabricated elements since the weight capacity in some locations were identified as being too costly to cover with the stationary cranes. The notation MK was used for mobile cranes, K for stationary crane and B for concrete trucks and pumps (see Fig. 3). These notations were also added in the modeled resource objects, respectively, together with the locations they covered. Some activities were altered to contain both a K and a MK, indicating that they could use either resource, though that the first listed were preferred if available.

All machine and equipment object parameters were stored in a schedule and hence automatically incorporated into the PID. The machines' unique IDs were hereby automatically connected to their corresponding activity, dependent on the activities defined requirement and location. If the activity contained two crane alternatives, the resource was first connected to the preferred alternative, although if this resource was already booked for another activity during the same time period, the secondly preferred resource was connected instead.

2.7 Analyzing how the specified resources are utilized ⑧

The PID contains specified information regarding the resource usage once step ⑦ has been performed, thus resource utilization charts can be automatically established for each *specific resource* of the same type as Chart B in Fig. 8 and Chart A in Fig. 9. Since the PID know exactly which resources that should be used, when in time and at which locations they are needed; double booked cranes and possible logistical issues can also be listed and reviewed. The PID now also contains information about the amount of fencing, waste containers, storage containers, barracks, and entrance gates required.

2.8 Identifying logistical, space and safety issues in a full simulation ⑨

All planning data and models have been rendered and connected by means of their unique IDs through the PID in previous steps ① - ⑧. Hence a full simulation including object erection, site-equipment and machines can be generated as a byproduct, skipping the tedious process of manually connecting activities, resources and modeled objects. This is done by simply adding the models and project plan (from the PID) to the simulation software and applying a rule connecting activities and modeled objects through the unique IDs. Fig. 12 shows some issues visualized in the full simulation: [A] a collision between the stationary crane and mobile crane, [B] a mobile crane being booked in two different locations simultaneously, [C] a mobile crane being overbooked, [D] an issue with access route for the mobile crane since the stationary crane is blocking the entrance.

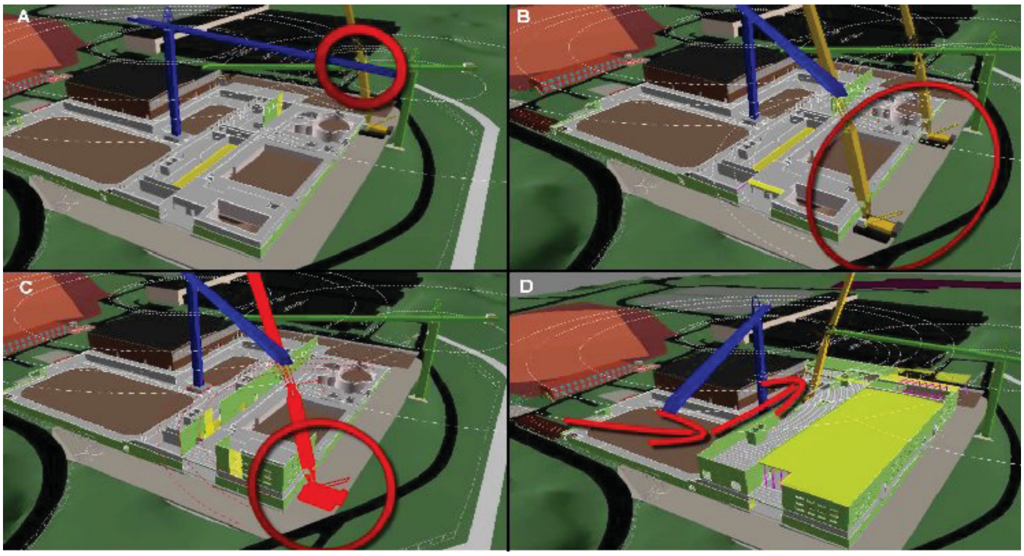

Fig. 12: Screenshots from the full simulation in the software Navisworks, highlighting visualized issues

3. Conclusions and Recommendations

With the described system and process it becomes easier to grasp the dynamic nature of on-site logistics, resources, equipment and machines related to time as well as space. Since the information is structured and placed into its context where it can be analyzed, actions can be taken to reduce the waste. The processes involved in planning and organizing the production do not necessarily take longer time, the difference is that information is gained and added digitally, which places the focus on adding valuable data rather than gaining and distributing information. If space or safety issues are identified, it is possible to change the project plan, production method or resources accordingly. Also, since more comprehensive and precise analyses can be gained earlier, it is possible to adjust the design gaining a more resource efficient production, optimizing the utilization of resources and lowering costs. The experiences gained are that the burden of work is not to add information which can be used to render refined analyses but rather to figure out and develop the ways in which information is presented to guide the user. The possibilities are limited only to imagination, and should thus be prioritized.

Compared to traditionally adopted procedures within the construction industry, the suggested system entails an increased use of software for the purpose of planning activities, determining on-site distribution and required machinery. Thus an increased level of IT-competence is required within the organization responsible for managing the overall works, usually the main contractor or client. Due to its coordinating implication for activities which sometimes entails conflicting processes, this increased competence should primarily be adopted by the project planner in charge of scheduling the master plan. The project planner can thus, by means of the gained analyses tools, more efficiently unite the involved processes. Since using the system involves comprehending a wide range of detailed information, there is a need to also increase the project planner's role making him work in closer proximity to subcontractors, logisticians, site management and designers.

A project plan developed by means of the suggested method contains a high resolution of activities within the lower hierarchies. Hence it is possible to make the project plan à jour with the actual state on-site. Since the activities are connected to modeled construction elements and machinery a last planner (LP) can use its virtual implication to inform on-site personnel of the day to day activities and their corresponding space allocation on strategically placed monitors. The LP can also add text in the simulation software to further highlight issues for instance regarding if another entrance route should be used due to safety etc. This would help to pedagogically inform workers of activities which may affect their work. Since it can be difficult for site management to judge information's relevance for different professions or working teams, it would also make individual workers less constrained by if, how, to whom or when verbal information from site-management is distributed.

In the gained analyses of the applied project it was identified that charts are more suitable for resource utilization analyses whereas the visual simulation is more adopted towards identifying safety issues and space collisions.

If the described system is implemented, objects have to be differentiated in terms of their inherent function in order to establish the Object-family label which is added to unique objects. Although there are codes such as AMA and BSAB, they fail in the delivery of a simple yet intuitive naming of objects applicable to all projects. Whether a predefined nomenclature should be project, organization or industry standard is also unclear. A concern is that difficulties in properly differentiating the varying purposes of construction objects in a common nomenclature will occur. Thus our recommendation is that a description of the object's inherent function is added by the designer based on intuition. Further research is needed in order to contemplate upon the possibilities of using a common nomenclature. Also further studies need to be conducted that focus on how the project planner's IT-competence and role should be increased and whether an additionally required model coordinator ought to be integrated in the process. Also the process may need adjustment depending on procurement type.

4. Future Outlook

In this study, automated arrangement and linkage of activities based on location were performed partly according to the *defined desired location based production sequence* and partly according to the *simulation number*. To eliminate the process of manually typing the simulation number into the model and also to simplify the arrangement of the desired location based production sequence, it is suggested that production directions are defined in the PID in relation to a coordinate-system preferably in graphics by placing arrows indicating the preferred production direction in a floor/level plan view for different object families and locations. This can be achieved by extracting the coordinates in the center of the mass for each object and transforming the coordinates into the "newly" created coordinate-axis (defined production direction indicated by the arrow). The transformation can be achieved by means of programming a matrix-transformation function into the PID and adding the coordinates in two points of the model on the floor/level plan view used.

Another finesse that this work wanted to practically investigate was to add analyses of the internal transportation on-site into the process. To specify how this can be achieved, gypsum boards will be used as an example which is divided into six steps: ① The number of square meters that one batch of gypsum boards covers is added to each unique object (Fig. 4), hence the number of gypsum boards in different locations is gained. ② Once activities have been scheduled, information supporting decisions of where to place the material upon delivery and how many deliveries that are required is presented. ③ Modeled gypsum batches are then placed into the model at the delivery-points along with corresponding delivery trucks containing delivery date according to preferences and the supporting information. If the storage is not in close proximity to the point of consumption, transportation-route-objects are added. ④ When the modeled material data is transferred to the PID it gets connected to its corresponding object and thus activity data according to the locations specified by the objects point of consumption. ⑤ Hence it is possible to display if the specified deliveries covers the required material.. ⑥ When the full simulation is shown you will be able to identify if the internal transport, deliveries or stock areas for material will collide in time with other activities on-site.

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AUTOMATED SIMULATION SYSTEM FOR BUILDING INFORMATION AND ENERGY-SAVING DESIGN MODELING

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ABSTRACT: *In recent years, green buildings and energy-saving designs have gradually gained popularity. Their importance is not only on the harmonic coexistence between human and the Earth, but also on the reduction of energy consumption including water and other resources. Nowadays, many building designers use the existing energy-saving designs without knowing the actual effects of the designs.*
The level of energy-saving of a designed building can be scientifically evaluated and simulated using energy simulation software (e.g., eQUEST, energyplus, Ecotect, etc.). Taking eQUEST for instance, the required input data includes 8760 hours of sunlight intensity information, temperature, the exterior and interior design of a building, building materials, and the properties of materials. The building-related information mostly comes from BIM (Building Information Modeling) models, and the transfer of information from BIM models to energy simulation software is usually done manually. To minimize the required time for information transfer and to automate this process, this research will propose a system that could facilitate the information transfer between Autodesk Revit and eQUEST. Since eQUEST is recognized by LEED (Leadership in Energy and Environmental Design), a green building certification authority, and eQUEST's output is eligible for scoring in LEED EA Credit1, the proposed system in this paper will be of help in the acquisition of green building certificates.
In addition, the energy simulation software has to generate a base model for a green building (or energy-saving) design before scoring in LEED EA Credit1. However, the generation of a base model is time-consuming, with no tools in the market designed for this purpose. Therefore, how to automatically generate a base model for a green building (or energy-saving) design is also an objective that the proposed system wants to achieve.
Integrating the aforementioned functions, it is certain that the proposed system will become a powerful tool for green building designers.

KEYWORDS: *BIM (building information modeling), LEED, energy consumption, automation*

Introduction

In recent years, green building has become more and more popular. The importance of green building not only lies in its eco-friendly designs, but also in its focus on reducing building energy consumption, wastewater production, and so on (Yu Jian, Ben yi Chang 2008).

When designing green buildings, most designers only referring to or completely imitating other existent designs, paying little attention to the buildings' actual ability in saving energy (ZengXu-dong, ZhaoAng 2006). In some cases, the construction costs increased yet the possibility to successfully enhance energy efficiency remained doubtful. In other cases, the ability in saving energy of a building built by energy-saving materials and designs turned out to be worse than that without any special design. (Yoon, Y. J., M. Moeck, et al. , 2008)

After the proposed design is analyzed by simulation software such as eQUEST, energyplus and Ecotect, a baseline is needed to determine the quality of the design, or to be qualified in the EA credit section of the international green building certification LEED (Leadership in Energy & Environmental Design) First, the design model should be modified into a baseline model for calculation on the base of LEED criteria. Then the energy consumption is to be identified and be used as a means to calculate its energy efficiency (The formula: [baseline model annual consumption amount – design model annual consumption amount] ÷baseline model annual consumption amount×100%). However, establishing a baseline model is difficult and time-consuming and there is no tool yet to help solve this problem, either in Taiwan or in other countries. Therefore, how to establish the baseline model in a quicker way is an important issue.

BIM (Building information modeling) collects building data and knowledge from designers from various fields, and integrates these data into the building's life cycle. The designers are able to obtain the needed data and building information from the building information model to accomplish information sharing and reusing. In other words, the building information model serves as a database.

BIM has been widely applied. This dissertation proposes the concept, In which the author applied BIM to establish a basic and automatic system to resolve the above-said problems. User can apply the system and insert the building and weather information into the energy consumption simulation software (This research took eQuest as an example)so as to calculate the data of annual power consumption and comparable criterion modeling of LEED.

In addition, taking a further step to calculate the energy efficiency and score the EA Credit 1 points in LEED following the scores table will quickly and efficiently obtain the LEED certification and calculate the energy efficiency. Currently on the market, there are GBS(Green Building Studio) Website-Service and Autodesk Ecotect to calculate the energy efficiency. Revit can be sent to GBS through GBXML. User then sends back eQuest.But GBS cannot be made in baseline format of eQuest, besides the information of GBS is not accepted by LEED criteria.

As for Ecotect, into which Revit model can be imported, the analysis results are not accepted by LEED criteria as well. This study analyzed the data of annual power consumption, just like GBS and Ecotect, and, furthermore, calculates the energy efficiency and goals of the EA Credit 1 points in LEED.

Literature Review

At present, the scientific calculation by simulation software can evaluate the energy efficiency of proposed designs. For example, calculation by the eQUEST will needs information such as, a record of sunlight strength and temperature over 8760 hours, the exterior and interior appearance of the building, the material used, and the attributes, etc. The eQuest has been used to calculate the energy consumption in some cases, and it has been applied to construct the TMY2 weather information formats (8760 hours) of Taipei, Taichung, Kaohsiung, and Hsinchu (Lin and Huang 2004). But the building model in eQuest still has a lot of drawbacks and the process it will take is time-consuming, which is why the energy consumption simulation software is not so popular.

In addition, the scale of construction initiatives is increasing. To cater to the demand on information management of the project management teams, 3D, 4D and BIM(Building information modeling) and other technologies are booming. Among them, BIM will be the focus in the future. The current applications of BIM include cost evaluation, space clash analysis, scheduling, construction simulation, and building energy consumption simulation, etc. (Hartmann et al. 2008)

Problem Statement

To minimize the required time for information transfer and to automate this process, this research will propose a system that could facilitate the information transfer between Autodesk Revit and eQUEST. In addition, automatically generate a base model for a green building or energy-saving design is also an objective that the proposed system wants to achieve.

At last, this system will incorporate lifecycle costing in the developed system, to allow the user to be able to know the lifecycle cost of each energy-saving design and make the best decision. Integrating all the aforementioned functions, it is certain that the proposed system will become a powerful tool for green building designers.

Research Methodology

Autodesk Revit (BIM tool), eQUEST (energy simulation tool), and Microsoft Excel (data storage) will be integrated as the backbone of the proposed system to calculate energy-saving efficiency, LEED EA Credit1 scores, and lifecycle costs. Visual Studio/C# and RevitAPI (the Application Programming Interface provided by Autodesk Revit) are used for the integration of Autodesk Revit, eQUEST, and Microsoft Excel. For each green building design, the corresponding resource- or energy-saving efficiency (such as the savings on electricity, water, etc.) will be studied and/or experimented to facilitate the calculation of lifecycle costs.

Related software application and the development of prototype system

In this paper, an automatic prototype system was developed. Every item including walls, roofs, windows, floors etc., in the BIM (e.g. Autodesk Revit) has its own parameter. By reading the parameter and the database, the parameter was processed into the data format which was compatible in eQUEST. The design model was used to calculate the annual energy consumption. By switching it to the Baseline Model according to the requirements of LEED, the scores of LEED EA credit1 could be obtained by checking with the table. The software chosen in this study was especially important because Revit and eQUEST were integrated as a system by Visual Studio 2008 to establish the developing background with C# as program language and Excel as database (The system structure was shown in Fig. 1). The software used in the study were introduced as follows.

BIM software – Revit

The BIM (Building Information Modeling) is an integrated information model containing related building information and professional knowledge provided by designers in different fields. Any participant in the building process could get the needed information which was already been done or waiting to be finished. The purpose of sharing and reusing information could be achieved. Some engineering consultants companies in Taiwan had already used Revit in practical applications. Therefore, Revit would be much more convenient to use and lea rn than other BIM software. The API (Application Programming Interface) in RevitAPI provided by Autodesk Revit could expand the function of Revit. The prototype system proposed in this study would be used to read the parameters in BIM and incorporated with other software to achieve the research goals. The major task was to read the coordination of the replaced items and the parameters being adjusted and inputted when users were using Autodesk Revit as BIM. Another task was to show the results of energy-saving efficiency and LEED EA Credit1 on the user interface for users to choose the ideal options.

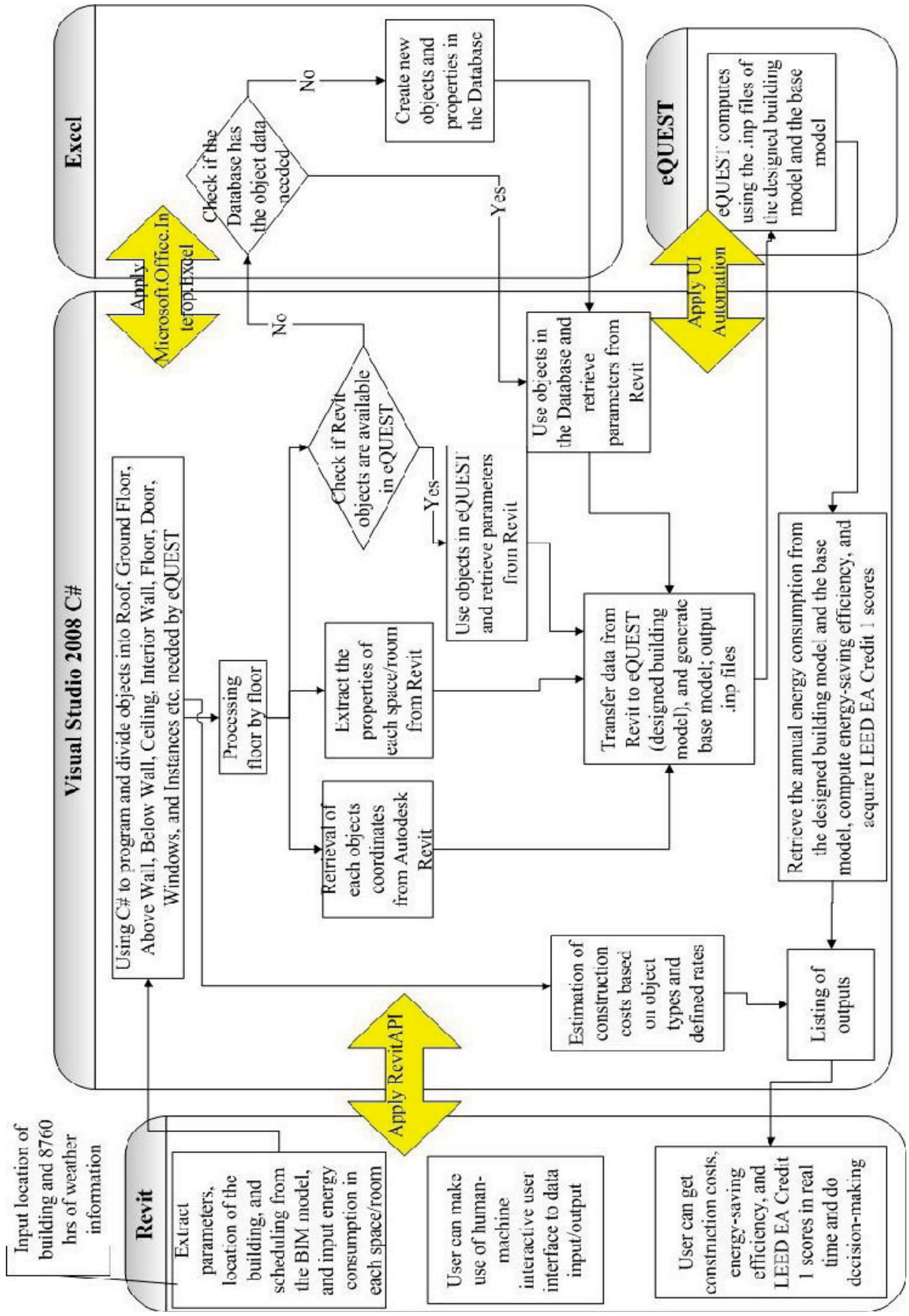


Fig. 1: Flowchart of System Development

Energy-consumption simulation software – eQUEST

The software used for energy-saving dynamic analysis in the study was eQUEST. The program was developed by Lawrence Berkeley National Laboratory and its cooperative partners and co-financed by United States Department of Energy and Electric Power Research Institute. It was freely-download and by continually updating, the eQUEST could maintain the reliability and fairness. The eQUEST had earned the public trust internationally and was widely adopted by energy and air-conditioning industry in Taiwan. By inputting the local climate data and the building information (location, size, appearance, location of windows, materials of the walls, and air-conditioning systems etc.) through graphical interface into the computing core DOE-2, the detailed annual 8760 hours' energy-consuming results could be analyzed. The hourly loading change of energy consumption could be known by the computing of eQUEST. Take some applications in Taiwan for example, every factory building in Taiwan Semiconductor Manufacturing Company was required to use eQUEST to simulate the energy consumption and got the LEED credit. One of the main reason to use eQUEST in this paper was because some charts in Evaluation Manual for Green Building Material (2009) was actually simulated by eQUEST, e.g., 3-4.3. Therefore, it would be much easier in Taiwan to learn the eQUEST. Another reason to use the eQUEST was because of the user interface (UI). Compared to DOE-2.2, it was easier to check if the input model and data were correct.

System Demonstration

The prototype of the experiment model used in this paper is the public housing design in Taipei, Taiwan (Fig. 2), and the Revit is used to design the BIM model (Fig. 3a). The time period for lightening set up for this prototype system is from 6 a.m. to 8 a.m., while that for using air conditioning is from 9 p.m. to 8 a.m. in the next day. When building model by Revit, the experiment room will only be furnished with equipments that will influence the energy consumption such as air condition and lighting.

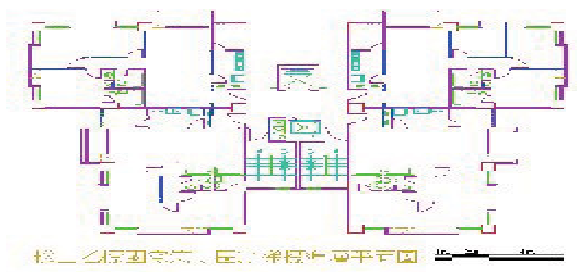
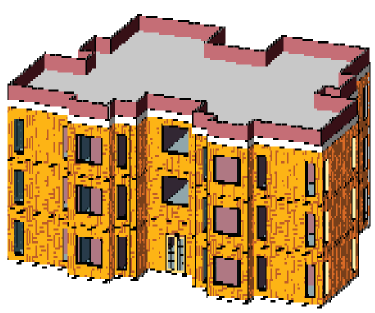


Fig. 2: The public housing design



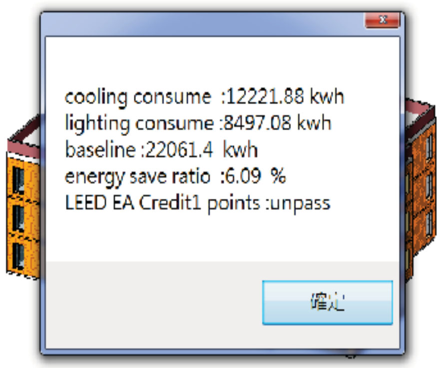
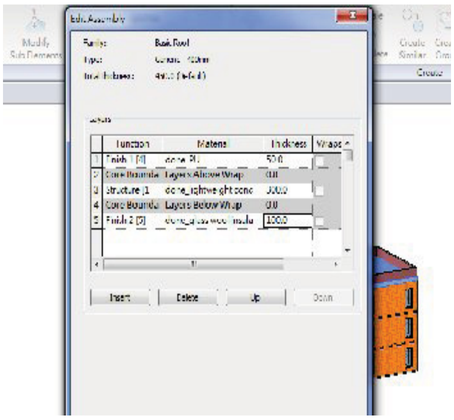


Fig. 3A: Model established by Revit *Fig. 3B: Execution results*

When the model is constructed, the researcher run the system and obtain the results shown in figure3.b.According to the results, the energy saving ration was 6.09% computed by LEED's standard. However, the requisite ratio in the LEED EA Credit 1 criteria should be over 10%. Therefore, more energy saving design is required for example, to thicken the glass wool insulation on roof(figure4.a.) The results of the second run conforms the LEED EA Credit 1standard, for the cooling consume actually decreases in figure4.b.



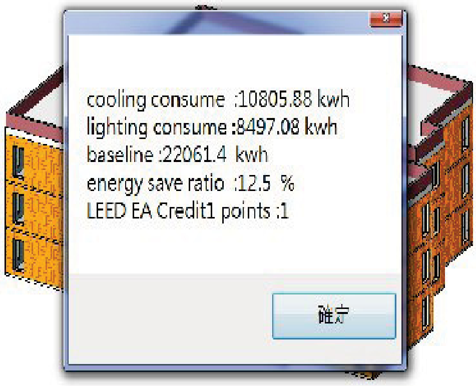


Fig. 4a: changing material on roof *Fig. 4b: execution results after changing material*

In this prototype system, when the site and size of windows or the materials of exterior walls are changed,or when the sunshading board is setup , the annual energy consumption and construction costs will all be influenced. However, this paper does not intend to show extensive description for each case.

Designers can make use of the prototype system shown in this paper when designing the energy saving system to design a LEED certified building, while taking customers' needs into consideration.

Conclusions and Recommendations

The prototype system developed in this paper was only to represent the concept and idea in the study. The only company who had the experience for both developing the BIM system and getting the LEED credits in Taiwan was Taiwan Semiconductor Manufacturing Company Limited (TSMC). Therefore, the project manager who was specialized in LEED credits in the new construction office of TSMC was interviewed in the study in order to fully realize the real applications of BIM and LEED credits.

Our company and the architect office would gather the information which was required in LEED credits to build the model in eQUEST and also deal with documents. If the prototype system was fully developed, it would be very useful because it usually took about a week, even a month, to build the eQUEST model.

By interviewing with the expert consulting with the concept of the present study, it could be concluded that the energy-saving design would be fast and effectively carried out after the system was fully developed and further acquired the LEED EA credit1. The time spent on planning how to reduce the energy consumption in order to get the LEED credit1 could be largely shortened. The process of making design changes could be simplified. Also, due to the non-slot process, the possible mistakes when inputting the information could be largely reduced compared to the procedure which was done manually.

Recently in Taiwan, there were several companies encouraging the related projects to use the energy simulation software. But the promotion of using eQUEST was not easy because it often took enormous time to build the eQUEST model. Except for producing engineering graphs, elevation graph, and 3D graphs, the design department also had to use eQUEST to simulate the energy consumption, which increased the difficulty for promoting the use of eQUEST. If the model was built using Revit to place the objects into the building model, all the graphs could be produced simultaneously. After the prototype system was fully developed, the building information could be transferred into the eQUEST, thus the BIM and energy simulation software could be widely applied in project use.

The energy simulation software could calculate the annual energy consumption of the building and the building cost per year, so it was suggested to integrate the life cycle cost NPV value into the future study, for it could be used as reference in terms of cost, energy-saving efficiency, and LEED EA credit1 for owner to choose the best design strategy. Recent application of BIM used in the early stage of evaluating the cost still had some difficulties. For example, different types and amounts of building objects in the model were not necessarily accorded with the actual building materials in the project. Sometimes the scaffolds and moldboards might be excluded in the model. Therefore, the building cost couldn't be accurately estimated if the model only calculated the objects built in the BIM model. It was recommended to carefully investigate the logical relation between the actual materials and the objects built in the model so as to accurately estimate the building cost.

This study was similar to the comments of the expert that there was still no specific way for users to input the schedule. Future researchers could take the study "A study on the energy consumption certificate of residential buildings" by Su (2009). The study formulated the schedule for residential use and also suggested to include the schedule of non-residential use"" in order to select the appropriate schedule for users.

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CROWD MANAGEMENT IN PUBLIC TRANSPORT – THE UTRECHT CASE

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ABSTRACT: *To ensure safe and comfortable circumstances for visitors in large buildings or urban areas, simulation is increasingly applied as evaluation tool. The increase is a result of both a growth in capabilities of the simulation tools and a fast growing recognition of the importance of crowd management and evacuation studies, based on tragic accidents in the last decades. With simulation, large-scale infrastructures can be studied under normal conditions to determine the quality of the daily transfer. But it is even more important to determine the performance in alternative situations or during an evacuation. In this paper the use of discrete event simulation for these purposes is demonstrated based on a case for the public transport terminal in Utrecht. The terminal will be completely renovated in the coming years, which results in continuous changing situations for travellers. This may however never cause compromises in safety and only as little as possible loss of quality of the service offered to the public. Based on the simulation results decisions are supported and some of the reconstruction phases have been modified to prevent the determined bottlenecks. Furthermore the simulation and animations work as a means of communication and have become important to expand the public support. The simulation trajectory itself has resulted into new research about modelling pedestrian flows.*

KEYWORDS: *Simulation, pedestrian simulation, crowd management, crowd control, evacuation, Public Transport, urban planning.*

1. Background

Recently a 20 year lasting reconstruction of a large part of the city centre of Utrecht, located in the middle of the Netherlands, has started. Due to the growth of the city and the undesirable current state, this so-called Station Area needs expansion of facilities and a thorough facelift to render it a safer and more pleasant place to work, stay and live in. The goal is to realize a new city centre for Utrecht by unifying the new Station Area and the old city.

An important element of the new Station Area concerns the renewal of the complete public transport terminal. The existing train terminal is nowadays used by 150.000 passengers per day and considered as heavily used. It is expected that in the year 2025 daily over 210.000 people will use this terminal as travel origin or destination and many thousands will use it as the link between the city districts, as shown in figure 1. Therefore the current infrastructure will be too limited to accommodate these numbers of passengers and an extension is required.

The new terminal will function as an integrated public transport system. It will not only cover all train platforms, including the High-speed Train tracks, but it comprises also two separate bus stations, a tram platform and a large transfer area. Adjacent to the terminal building large new office towers, a shopping mall and leisure centres are erected and several multi–level bike storage buildings will be developed to accommodate about 22.000 bikes.

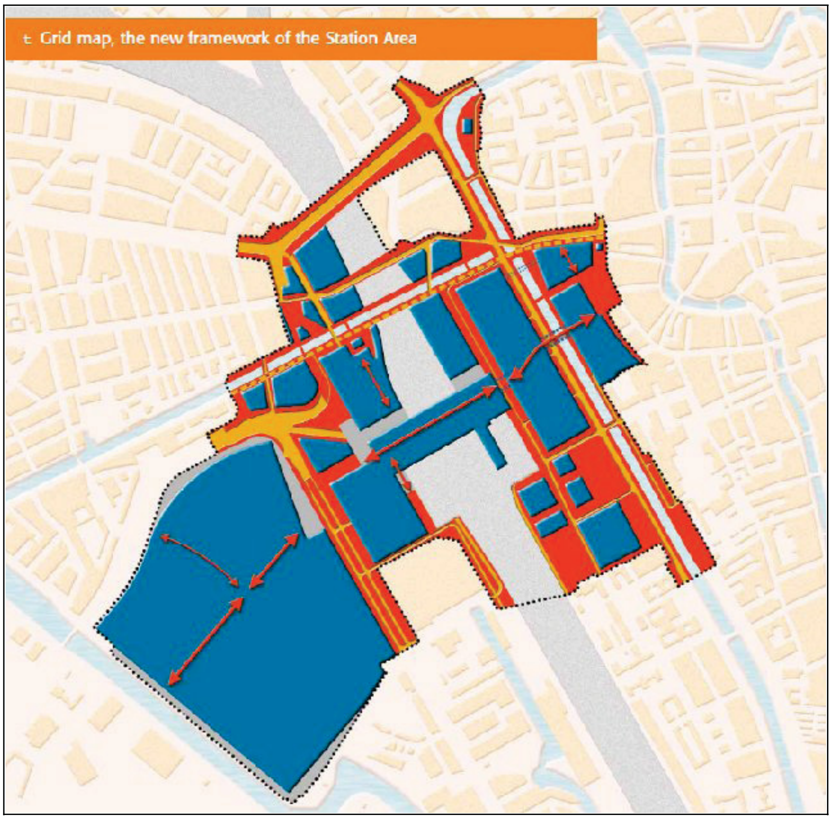

Fig. 1: Urban zones and connections framework (source: City of Utrecht, 2003)

2. The Challenge

Building such a terminal is already a tough labour, but it is a real challenge to do so while the daily transfer must go on and many involved parties have to work in and around the terminal. During each of the numerous stages in the building process it is required that different sections of the existing terminal have to be taken out of use to create new construction areas and to assure safe transfer areas. Obviously this will disturb the pedestrian flows, as pedestrians have to deal with new and restricted situations frequently.

In the Netherlands ProRail is responsible for maintenance and renewal of tracks and stations and providing capacity for their clients. Therefore they have commissioned the terminal building project and carry responsibility for both accessibility, safety and convenience in the terminal. Other involved organizations and authorities include the Dutch railways, the city of Utrecht and the building contractors. But also the municipal fire brigade, which demands that the terminal can be evacuated within certain time levels under all circumstances and that it does not affect the safety in the vicinity. Without approval from the fire brigade construction work or additional commercial units in the terminal will never be authorized.

Therefore these joint parties have to propose and evaluate possible measures to solve pedestrian flow disturbances and keep evacuation procedures valid during these construction phases. An appropriate instrument to test operational situations, to evaluate measures and their effectiveness and to present it all visually is pedestrian simulation.

The pedestrian simulation models will not only be used to convince decision makers about the need for certain measures by presenting performance indicators. Other important advantages are that the visualisation of situations and results can demonstrate the situations that could occur and that it can improve communication. The same visualisations can also be used to demonstrate the effectiveness of certain measures, even when they are just a simple 2D representation.

3. Pedestrian Simulation

Pedestrians moving through busy environments, like for example a public transfer terminal, experience constraints during their transfer. The effect of the constraints is that they have to adapt their walking speeds, especially when they have to deal with large crowds and opposing flows, they experience waiting times, may choose other routes or even change a destination. So the required transfer times will fluctuate and so does the quality of transfer.

Pedestrian dynamics research focuses on the question when, why and how people adapt their walking speed or walking directions. From research over the last decades it is concluded that many causes exist, ranging from quantitative aspects like densities and flow directions to more qualitative aspects like type of surface, noise level, colour or smell. And then there are differences between nationality, gender, and so on.

As the qualitative aspects are hard to model, most research has been performed in the field of quantitative analysis. Fruin (1971) has extensively described the relation between walking speeds, flow rates and area occupancies on walkways and stairs. Although several researchers have captured a relation between speed and density, see figure 2 from Daamen (2004), the concept of Fruin with the accompanying Level of Service system is still the basis for many pedestrian research and simulation models, as it offers an intuitive way of visualizing and judging a crowd's performance.

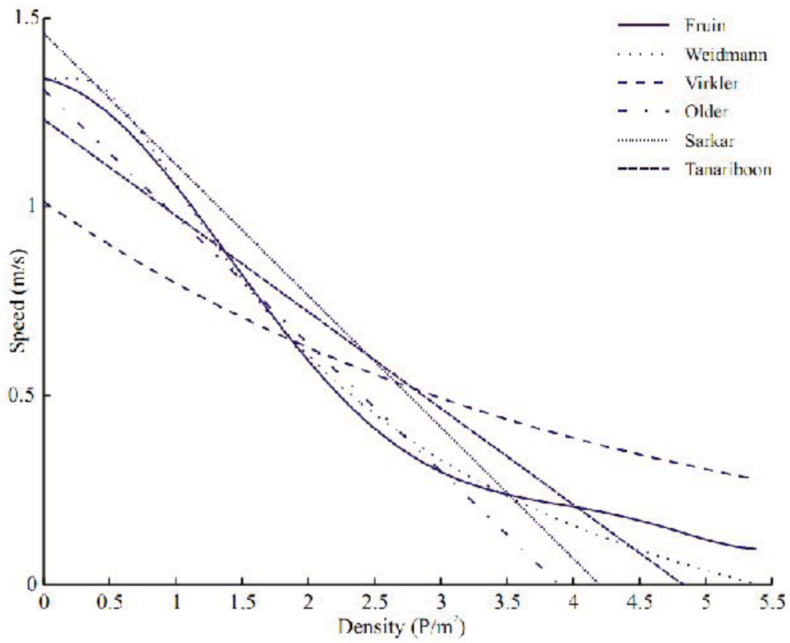

Fig. 2: An overview of speed-density relations

The speed density relations are the basis for the mesoscopic simulation approach, in which pedestrians are modelled as individual object with their own desired speed, behaviour and routing. The pedestrians use networks, composed by nodes and walking paths, to reach their next destination through a pre-defined route. During each event (or time step) the speed of individuals can be adjusted based on the densities in the area they are in. In more advanced mesoscopic models it is even possible to change the routing when faster routes can be found.

Other simulation approaches are macroscopic simulation and microscopic simulation (Tauböck 2005). In the macroscopic approach the pedestrian movements is represented as a flow through space. With mathematical models that resemble fluid dynamics models, the behaviour of the combined behaviour of pedestrians in a group is described.

In the microscopic approach each pedestrian is represented individually. The individual entities have a unique behaviour, but unlike the mesoscopic approach, the mutual behaviour of pedestrians, like collision avoidance, is also taken into account. Two main groups of microscopic models can be distinguished, the continuous approach (e.g. social force) or the discrete approach (e.g. cellular automata).

A new kind of approach is described in Moussaïd (2011). This cognitive science approach is based on behavioural heuristics, that uses some simple procedures. This method is very promising to be applied in simulation, but it is still under research.

Microscopic models often use a type of continuous simulation, in which the environment of pedestrians is monitored continuously and its behaviour is adapted instantly. Microscopic research is mainly used for detailed representation of pedestrian behaviour in relatively small areas. Due to the continuous monitoring of pedestrians and environment, the required computer processor capacity of these models is very high. For that reason large-scale microscopic simulation models are still rare. Another reason is that these detailed models require very detailed input data and are hard to validate.

Since mesoscopic simulation applications are well capable of dealing with large numbers of pedestrians and large scale routing networks, they are very suitable for modelling large infrastructures such as a public transport terminal, in which several ten thousands are present at the same time.

For the case presented in this paper the discrete event simulation tool Enterprise Dynamics PLATO is used, which is one of the mesoscopic approach tools.

3.1 Routing algorithms

The routing of pedestrians in the model is one of the most important aspects. The foundation for the routing is a pre-defined activity plan. For passengers in a terminal there are always mandatory activities that have to be performed, like buying tickets, passing a control gate or walking to the platform. Other activities, like visiting a shop, are voluntary, but can also be part of the routing. In our approach chances, based on historical data, are used to assign these voluntary activities.

The widely used A* search algorithm determines the optimal path between two points in the network, by using cost values for each path and a heuristic function that estimates the remaining path length to the goal. The basic cost function is according to the Dijkstra algorithm (Dijkstra 1959) which performs *shortest* path calculations. However another approach is to use a cost function in which the density in the areas on this path is taken into account. With the speed density-relation as described before, expected travel times are evaluated to determine the *fastest* path.

For the routing from current position to the next destination the algorithm is evaluated each time a person enters a new node in the network. In that way we allow re-planning of the route. That can even lead to selecting new destinations, in case the person can choose from several equivalent activities (eg. several ticket machines or ticket control gates).

Special routing scenarios have to be used for modelling specific scenarios like evacuation and a calamity.

During a terminal evacuation all passengers in the terminal have to walk to an emergency exits. In many occasions the number of emergency exits differs from the regular exits which creates other routing options. Based on expert opinions two different ways of selecting an exit are tested: running to the original entrance (a well known location) and taking the closest exit, based on emergency signs. Both methods can be used separately or in combination, to evaluate the evacuation performances.

For a calamity situation, such as a train failure it is assumed that the passengers in question go to specific designated sections in the terminal to wait and get informed, while other passengers keep on transferring as normal.

3.2 Performance indicators

The different construction phases are judged by setting up scenario's in the simulation study. For every scenario the performances are expressed in many performance indicators. The most important are:

- Evacuation time distributions: for all emergency exits the number of evacuees and their exit time are collected.
- Throughput times between origins and destinations:
- Waiting time distributions at several restricted facilities: for evaluation of the facilities in the terminal
- Flow intensities (throughput per time unit) on specific screen lines
- Densities (occupation of areas) and accompanying levels: the main indicator used for judging the quality and safety of the terminal under normal circumstances.

In the simulation application used for this case study, the values for all of these indicators are collected during the simulation time and the averages and maximum are presented in a results overview. These performance indicators are compared to the formulated levels to evaluate whether the flows are acceptable or thresholds are crossed on specific locations.

4. The Public Transfer Terminal Utrecht Case

4.1 Study area

The case study concerns the new public transfer terminal of Utrecht, which will have the 'all under one roof' concept. The platforms for trains, trams and busses are on the ground floor, the terminal building itself is one level up. Several stairs, escalators and elevators give access to the platforms. The terminal building is the connecting layer for transfer between modalities. Figure 3 presents a design impression of the building.

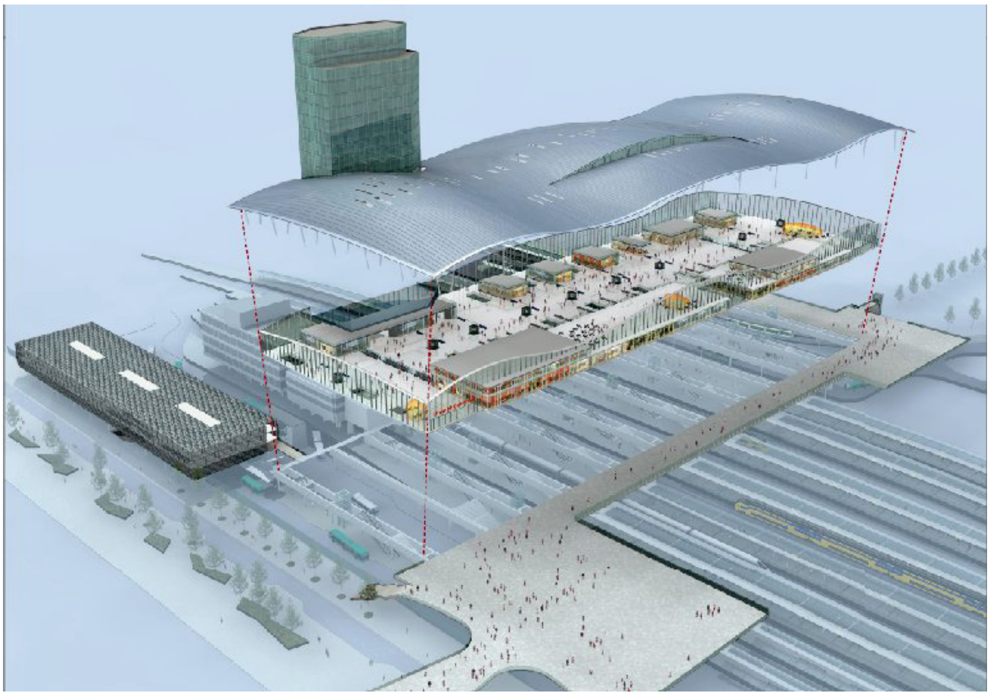

Fig. 3: Terminal design (source: ProRail / Benthem Crouwel architects, 2007)

In the study not only the final situation around the year 2020 is evaluated, but especially the trajectory towards this situation. Between 2010 and 2015 several building phases occur with restricted space and flows and each of these phases consists of numerous situations. For each of the situations a model has been created, describing the actual situation in that phase in terms of accessible platforms, stairs, escalators, transfer areas, etc.

These models comprise the complete infrastructure and pedestrian flows in the train terminal and the arrivals from and departures to and from other means of transport. Elements of the models are:

- The terminal hall with all facilities such as ticket sale, kiosks, shops and the chip card gates
- The passage lane for pedestrians who use the station for transfer between the eastern and western district without passing gates.
- The tunnels under the platforms leading to and from the other means of public transport (tram, bus, taxi) and the city (by bike or foot)
- The available platforms for trains, busses and trams, including their connection to tunnels and terminal hall through stairs and escalators
- The entrances and exits of the pedestrians, e.g. the eastern and western bus terminal, tram platform, bike storages and entrances from/exits to the city districts where people come from or go to by foot

During each of the construction phases, elements of the infrastructure, e.g. entrances, tunnel sections or stairs, will be closed. In order to see the effect of these works and measures to reduce consequences, especially during peak pressure, it is necessary to simulate the terminal in detail. Therefore the models are scaled representations of the available infrastructure, including marked building areas.

The terminal model is set up modular to enable linking to other modules. Recently the model is extended by joining modules for a large bike storage and the two big forecourts, so that the scope is expanded and the interaction between different modules in the reconstruction of the Utrecht Station Area can be shown.

4.2 Data collection

The occupation of every part of the terminal is very dynamical, then it is very dependent to the peak flows of travellers. During the day one can off course distinguish common rush hours in the morning and the afternoon, but the largest dependency is on the different schedules. An arriving train, tram or bus causes periodic crowds at the platforms, on the escalators, in the tunnels and halls and in front of chip card gates, but minutes later all can be calm again.

For the purposes of this study - to determine whether there is or can be enough transfer capacity to handle the passengers in a safe and acceptable way - it is enough to focus on the rush hours in morning and afternoon. Therefore the required input data is collected for these periods.

The input comprises:

- the timetables for the different means of transport (train, tram and bus), including the transport material and exact halting locations
- The expected load per transport (amount of travellers), based on counts and numbers from forecasting tools, all validated by ProRail and the other stakeholders.
- Dimensions of all elements in the infrastructure such as widths of stairs, passages and platforms.
- Distribution in use of entrances, exits, origins and destinations
- Use of facilities like ticket machines, shops or kiosk
- Levels for safety and quality that have to be met

The information is collected from several data sources provided by the project stake holders and expanded with results from counting and measuring studies. All information is linked to each other in a large database-application that creates the model input. As a result the model generates all trains and vehicles and the expected 110.000 pedestrians per 2 hour peak. Each of the pedestrians is assigned a creation time, an origin (entrance, platform), a destination (exit, platform), an expected route (including activities) and in case of a transport destination an estimated time of departure.

4.3 Results

To show the results of dealing with these 110.000 pedestrians in a 2 hour peak in the model, the status of the model components is monitored continuously. In the animation the density of every walking area, stairs and escalator is indicated by colours, each representing a density level. These densities are also stored in order to be able to show the progress over time afterwards. For reporting purposes the maximum density per area during simulation time is captured in one picture, as demonstrated in figure 4.

Besides a viewer is developed to replay the model, without actually simulating. It can just plays the logged states for all elements per time interval without requiring simulation software. These images prove to be very valuable in communicating the results to involved parties and even the public.

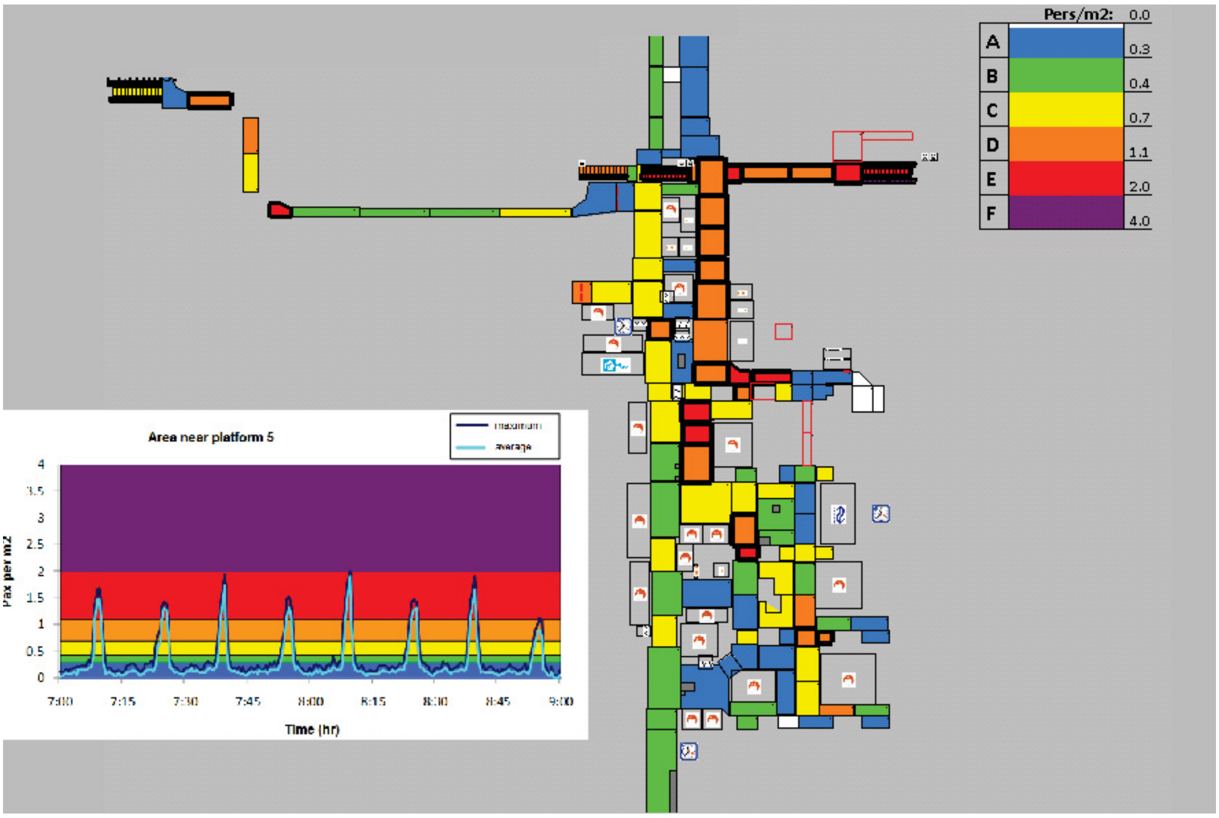

Fig. 4: Density overview terminal level 1.

Other results of the model are tables, figures and graphs of the other performance indicators for every scenario. These concern the flow counts on screen lines in the model (in persons per minute), waiting times in front of each of the faculties, especially the chip card gates, which are new in the terminal and number of passengers in each of the terminal segments.

The travel times between origin and destination are monitored and displayed, again during the day.

Special attention is given to the performance of the evacuation scenarios, as they are used for gaining permission to carry on building. This means that distributions of evacuation time per exit are provided and discussed with the fire brigade.

4.4 Validation and real life tests

An important stage in a simulation project is the validation of the model. This is not an easy task when it concerns a complete new situation with passenger profiles that are not exactly known. In that case one has often to fall back on using available measurements and expert validation.

However, in this project several real life tests have been performed during different building phases. The results are not only used for validation of the simulation models, but also to test whether the predicted results of the measures against detected potential bottlenecks, such as relocating fences or introducing crowd control, are in line with the expectations.

In addition ProRail has, parallel to the simulation, initiated a project to improve the knowledge of how the terminal is being used by the passengers. For that reason several monitoring systems are tested and used, including counting, Bluetooth tracking and camera systems with software to separate individual persons to determine densities, speeds, directions and staying times. Figure 5 shows a representation of these images.

The results of this CCB Analyzer camera system are not only perfect for validating the model by comparing results, it is also a huge source of information about the system input as they provide data for several weeks and 24 hours per day. For example the differences between the weekdays appeared to be quite remarkable. The results also tell a lot about the behaviour of passengers in the terminal. That information is used to further improve the model so that future model output can be even more accurate.

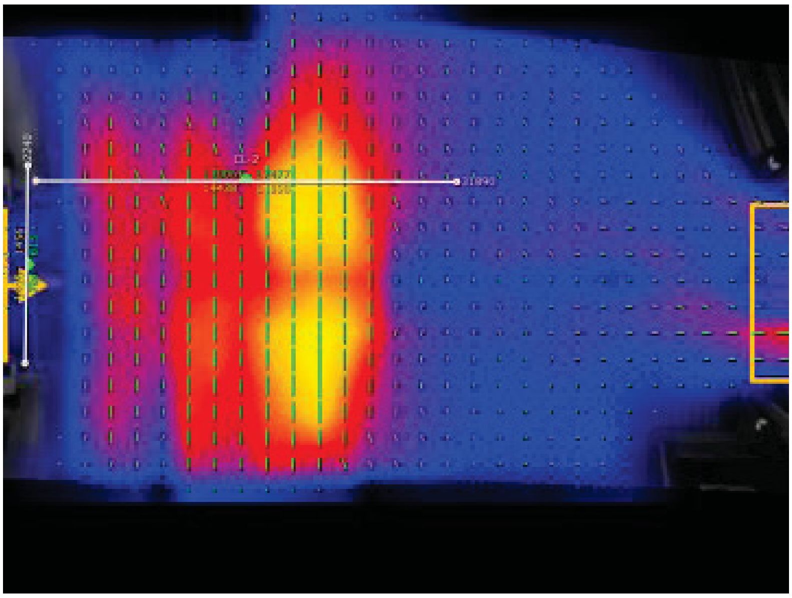

Fig. 5: Camera density scan

5. Conclusion and Outlook

Simulation and visualization have proved their value in this project several times and the large numbers of people were no problem for this mesoscopic model. The results have not only resulted in taking measurements like changing escalator directions in specific periods, signing and active crowd management, but it has also contributed to (minor) changes in the construction phasing. When bottlenecks were detected the model has been used to determine which measure is effective or what transfer width is required. The recent real life tests with counting methods and camera recordings during the first construction phase have been used to improve the models, but they also confirmed the predictive value of the model.

The animation and replay functionality have been used as means of communication and is presented to all stakeholders. As a result the simulation has gained such a confidence amongst all project partners, that no decision in the construction phasing is done without first evaluating it with the simulation models.

Another result is that the questions in return are getting more detailed. For some issues the focus is on such a detailed and isolated segment, that a microscopic approach seems to be necessary. As it is not desired to apply the microscopic approach for the complete environment (this would require microscopic input and human behaviour), the future research focuses on a hybrid approach with mesoscopic simulation and the ability to zoom in on a segment on microscopic level.

A next part of the research is aiming at increased automation of the model set-up and routing networks and rerouting algorithms. Ideas as the indicative routing method as presented by Karamouzas (2009) seem to be fitting as a basis for the proposed approach.

Finally new visualisation methods for such large environments in VR mode are under research. With a potential new standard as CityGML for 3D infrastructure models and the extensive geometry descriptions in the building information model (BIM) and its exchange standard IFC, several short-term developments are foreseen.

6. References

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DEFINITION OF OPERATIONS ON NETWORK-BASED SPACE LAYOUTS

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ABSTRACT: *Network-based space layouts are schematic models of architectural spaces for building design. They adopt a space-centered view and incorporate aspects of existing architectural space models. A layout has a geometric network that represents certain spatial relations between layout elements. A network may be analyzed using graph algorithms, such as nearest neighbor or shortest path algorithms. Operations on network-based space layouts are defined that are closed, that is, they derive consistent layouts from given consistent layouts. Closed layout operations may be composed into expressions. This facilitates the derivation of multiple views of buildings. An example of a layout operation expression is presented in which a lighting-specific layout is derived from an existing layout.*

KEYWORDS: *Architectural space models, Building information models, Query languages*

1. Introduction

Space layouts are used in architectural design to model the spatial configuration of buildings. Space information in layouts is relevant for applications in various domains. For example, building services designers reuse space layouts created by architectural designers to develop heating, ventilation, and air conditioning (HVAC), lighting, access control, and security systems. Several layout representation methods exist to support the analysis of space properties, or the generation of alternative layouts with respect to functional and spatial requirements (Steadman, 1983, Hillier and Hanson, 1989, Liggett, 2000). These methods typically explicitly model space proximity, adjacency, or access relations. This modeling approach has been extended to more fine-grained layouts which are referred to as network-based space layouts (Suter, 2010a). In addition to regular spaces or whole spaces, a network-based space layout models subspaces and space elements, such as walls, openings, furnishing, or technical equipment elements. Selected spatial relations between layout elements are represented explicitly in a directed, weighted graph or network.

The structure of network-based space layouts may be analyzed with graph algorithms (Bondy and Murty, 2010), e.g. to determine the shortest path between two circulation subspaces, or to classify whole spaces and subspaces as adjacent to a building's perimeter (Suter, 2010a). Similarly, query languages such as SQL (ISO/IEC, 2008) may be used to extract data from layouts. Although sufficient for simple queries, such layout operations are not closed, that is, they do not generally result in consistent layouts (Suter, 2010b). Closed layout operations may be composed into expressions. The objective of this paper is to define layout operations that are closed and appear particularly useful for building design.

2. Review of Network-based Space Layout Concepts

2.1 Layout elements and layout element relations

Layout concepts that are relevant for the definition of layout operations are reviewed in this section. Detailed descriptions are provided in Suter (2010a) and Suter (2010b).

Network-based space layouts are schematic models of architectural spaces. They adopt a space-centered (as opposed to an enclosure-centered) view and incorporate aspects of existing architectural space models (see, for example, Bjoerk, 1992, Eastman and Siabiris, 1995, Ekholm, 2000, BuildingSmart, 2010). A layout consists of four types of layout elements (*le*): whole spaces (*ws*), subspaces (*ss*), space boundary elements (*sbe*), and space elements (*se*). A whole space is a space which is bounded on all sides by space boundary elements. A space boundary element is part of an immaterial layer with zero thickness that bounds a whole space. A partial space or subspace is a space which is contained in a whole space. It may or may not be bounded on all sides by space boundary elements and may surround space elements. The latter are (physical) objects, including windows, tables, or luminaires that are either contained in or enclose a whole space. Space elements have attributes that indicate if they are whole space contained or whole space enclosing space elements (*cse* or *ese*). A desk is an example for a *cse*, a door for an *ese*. The distinction of *cse*s and *ese*s matters because they participate in different spatial relations.

A layout has a layout element network, which is a directed, weighted graph with *le*s as nodes and spatial layout element relations (*ler*) as edges. *Le*s and *ler*s have weights, which facilitates layout analysis with graph algorithms. Spatial relations in an *le* network include certain adjacency, boundary, surrounds, and proximity relations between *le*s. These relations are illustrated with an example layout (Fig. 1). As they are difficult to visualize together, relations are shown as partial views of the same layout. Moreover, space volumes are offset in Fig. 1b.-d. for improved visualization. Volumes may actually touch, as in Figure 1a.

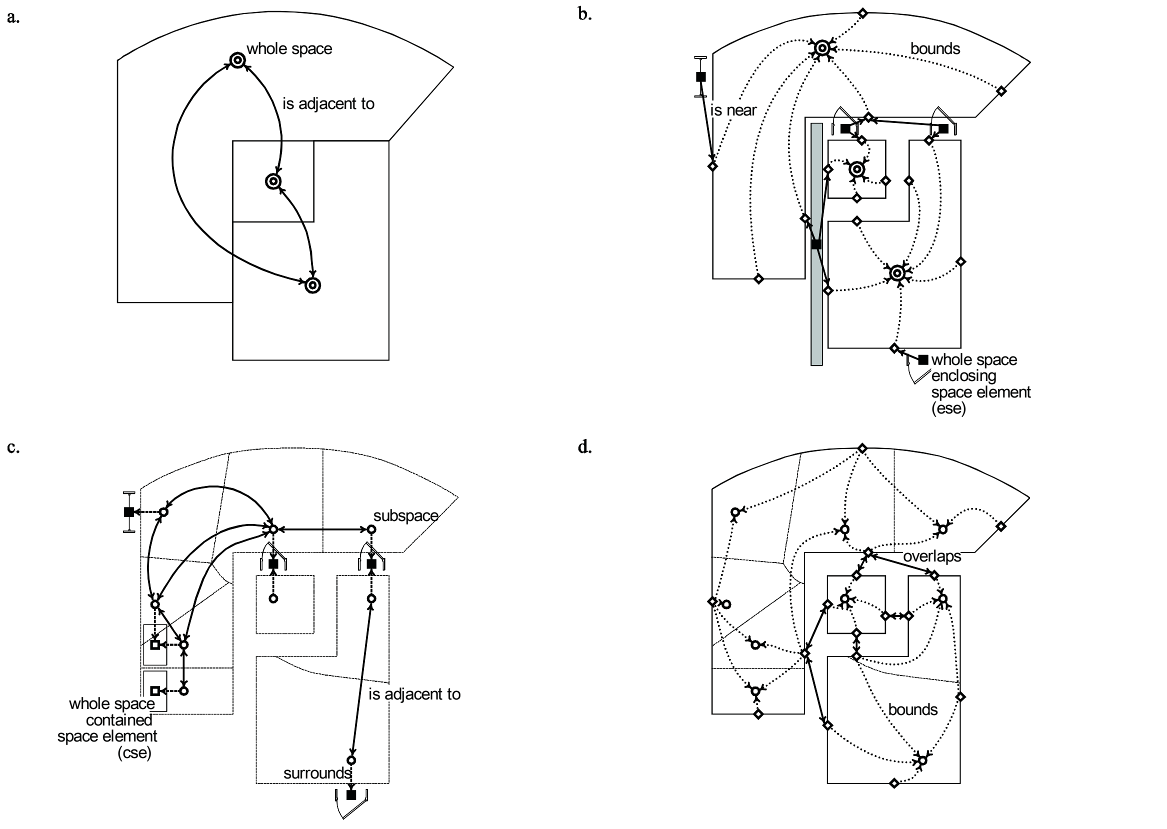

Fig. 1: Spatial relations in a network-based space layout. a. Adjacency relation between whole spaces (A_{WS}), b. Boundary relation between sbes and whole spaces ($B_{SBE,WS}$) and proximity relation between ses and sbes ($N_{SE.SBE}$), c. Adjacency relation between subspaces (A_{SS}) and surround relation between subspaces and ses ($S_{SS,SE}$), d. Boundary relation between sbes and subspaces ($B_{SBE,SS}$) and overlap relation between sbes (O_{SBE}).

In the layout in Fig. 1, subspace volumes are disjoint and fill the volumes of containing whole spaces. These subspace volumes are geodesic Voronoi cells that are generated with subspace positions and whole space volumes used as, respectively, sites and obstructions (Aurenhammer and Klein, 2000). Each point inside a subspace volume is nearer to the subspace node than to any other subspace node. Given a position (e.g. of a person), one can thus easily find its nearest subspace node. Other subspace volume derivation methods are supported, but these are not present in the layout.

2.2 Layout refinement

Spatial consistency of layouts is relevant for layout operations. A spatially consistent layout meets certain constraints on explicit and implicit spatial relations between *le*s (Suter, 2010b). As an example for an implicit constraint, no pair of whole spaces in a layout may overlap.

The conversion of a possibly inconsistent layout to a consistent one is termed as refinement. A refinement routine that uses constraints to identify and resolve spatial inconsistencies in layouts has been outlined in Suter (2010b). Fig. 2 illustrates spatial inconsistencies in a layout and how they are resolved by the refinement routine. For example, there is a desk in the unrefined layout (Fig. 2, left) which is not contained in a whole space and is thus removed. There is another desk in the down right whole space, which, according to its type definition (template), is surrounded by at most four subspaces. Two subspaces are feasible but not present. These missing subspaces are inserted (Fig. 2, right). As a consequence of the insertions, volumes of subspaces in the down right whole space are inconsistent and must be (re)generated together with subspace adjacencies. These and other inconsistencies of *le*s and *ler*s are resolved in the refined layout.

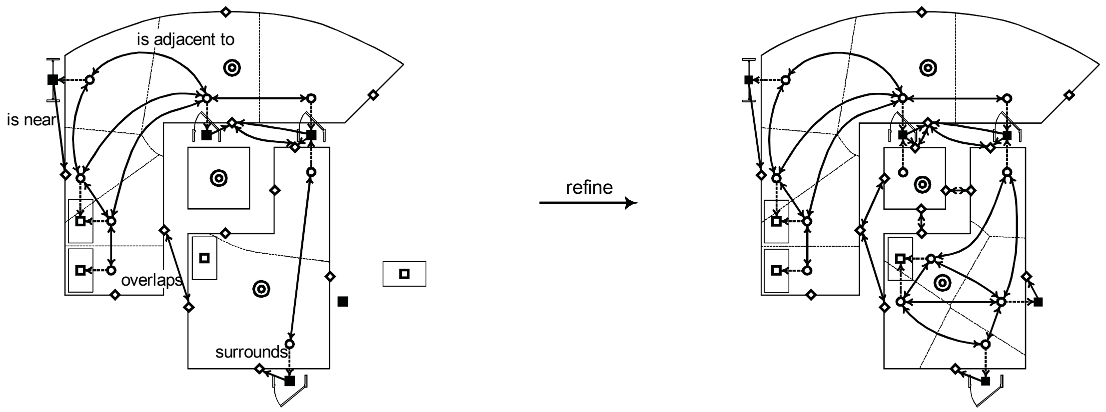

Fig. 2: Illustration of the layout refinement routine. A_{WS}, $B_{SBE,WS}$, and $B_{SBE,SS}$ relations are not shown.

3. Layout Operations

3.1 Overview

Layout operations are introduced, including *select*, *aggregate*, *decompose*, and *update*$_{WEIGHT}$ operations. Their signatures and processing are defined and illustrated. Variants with different signatures are conceivable for each operation but not described here for space reasons. Each operation is closed, that is, it accepts a consistent layout as an argument and returns a consistent layout. Spatial consistency of result layouts is ensured by layout refinement (Section 2.2), which is the last step in the processing of *select*, *ag-*

gregate, and *decompose* operations. Refinement is not required in case of the $update_{WEIGHT}$ operation as it does not modify structure or geometry of argument layouts.

3.2 *Select* operation

The *select* operation selects *le*s from the argument layout *E* based on predicates on *le*s in *E*. For example, a layout consisting of whole spaces that are offices may be selected with the *select* operation from an argument layout that also includes service rooms and circulation spaces. The operation has the signature

$$select_{P_{LE}}(E)$$

where

- $P_{LE} = (p_1(LE_1), p_2(LE_2), \dots p_n(LE_n))$ is a list of predicates on attributes of les in E – targeted les are selected, and
- E is a layout (a layout operation expression).

If there is a predicate on whole spaces in P_{LE}, then whole spaces are selected explicitly. If not, then whole spaces are selected implicitly if they are related to selected *le*s. This is because *le*s that are not whole spaces are dependent on whole spaces. For example, a furnishing element that is not contained in a whole space is considered as inconsistent (Section 2.2). Similarly, if a space element is selected explicitly but not its surrounding subspaces, then these subspaces are selected implicitly (and vice versa). The operation does not support predicates on attributes of *ler*s because *ler*s are derived from *le*s. Operation processing involves these steps:

1. A relational algebra selection operation (Silberschatz, Korth, and Sudarshan, 2006) is created and executed for each $p_i(LE_i)$ in P_{LE} to select *le*s from the argument layout *E*.
2. If there is no predicate on whole spaces in P_{LE}, then whole spaces that are related to selected *le*s are selected. A whole space *ws* is related to a layout element *le* if
   - *ws* contains *le* (*le* is a *cse* or a subspace),
   - *ws* is bounded by *le* (*le* is an *sbe*), or
   - *ws* is bounded by an *sbe* that is near *le* (*le* is an *ese*).
3. If there are selected space elements that are surrounded by unselected subspaces, then these subspaces are selected (and vice versa).
4. The intermediate layout is refined into the result layout (Section 2.2).

Examples of the *select* operation are shown in Fig. 3. In the first example (Fig. 3, top right), all whole spaces are selected from the argument layout (Fig. 3, top left). *Sbe*s and *ler*s are derived when the intermediate layout is refined.

In the second example (Fig. 3, down left), whole spaces that are *WORK* spaces and all *se*s are selected from the same argument layout. The cabinet in the *CIRCULATION* whole space is initially selected but not contained in a selected whole space. It is therefore removed when the intermediate layout is refined. Subspaces are selected implicitly if they surround selected *se*s.

In the third example (Fig. 3, down right), there is no whole space predicate. That is, whole spaces are selected implicitly if they are related to selected doors or subspaces.

The predicate $_{width<0.9}(SE \bowtie DoorT)$ targets space elements that are doors (instances of type *DoorT*) and less than 0.9 m wide. The ⋈ symbol stands for the natural join operation in relational algebra. A stand-alone subspace in the left whole space in the argument layout which does not surround a space element is selected as well.

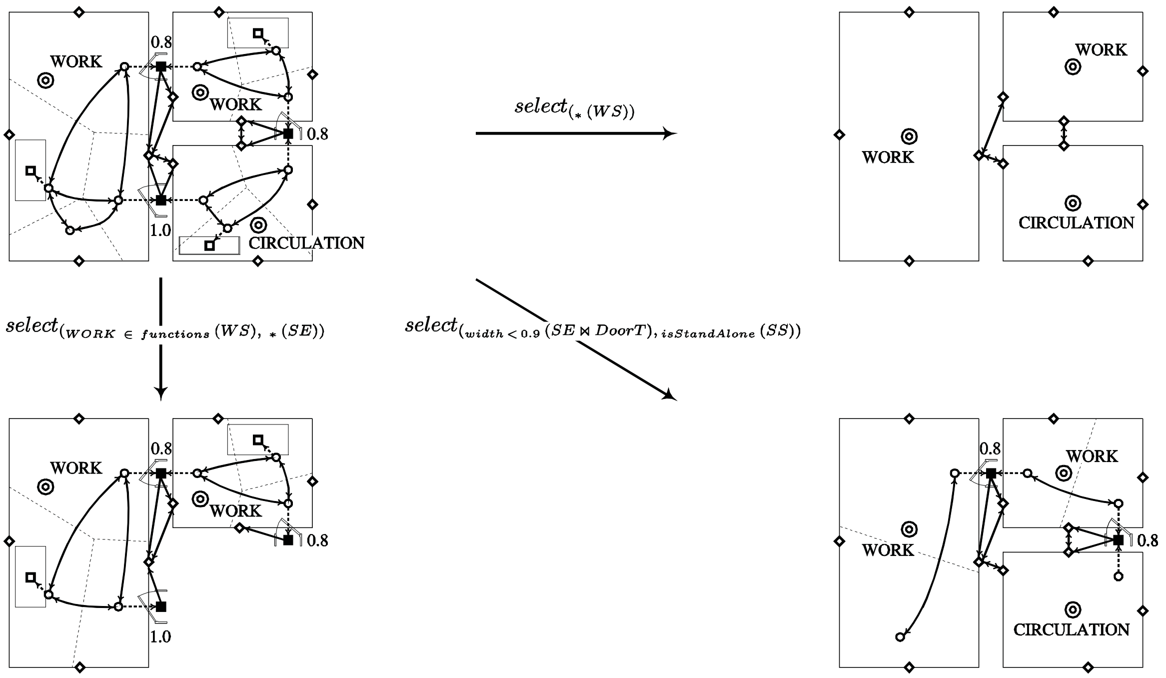

Fig. 3: Examples of the select operation. A_{WS}, $B_{SBE,WS}$, and $B_{SBE,SS}$ relations are not shown.

3.3 *Aggregate* operation

The aggregate operation merges sets of whole spaces in the argument layout *E* into larger whole spaces. Whole spaces in a whole space set belong to the same group (as specified by given whole space attributes) and are connected in a subnetwork of the *le* network of *E* (as specified by given predicates on barrier *le*s and *ler*s). For example, the *aggregate* operation may be used to derive a layout with whole spaces that result from merging whole spaces with the same function in an argument layout. The operation has the signature

$$aggregate_{G_{WS},\,P_{LE_b},\,P_{LER_b}}(E)$$

where

- $G_{WS} = (g_{ws_1}, g_{ws_2}, \ldots, g_{ws_k})$ is a list of whole space attributes that are used to group whole spaces in *E*,
- $P_{LE_b} = ({}_{p_1}(LE_1), {}_{p_2}(LE_2), \ldots, {}_{p_n}(LE_n),)$ is a list of predicates on attributes of *le*s in *E* – targeted *le*s are used as barriers,
- $P_{LER_b} = ({}_{p_1}(LER_1), {}_{p_2}(LER_2), \ldots, {}_{p_m}(LER_m),)$ is a list of predicates on attributes of *ler*s in *E* – targeted *ler*s are used as barriers, and
- *E* is a layout (a layout operation expression).

Whole space grouping is analogous to grouping in aggregation operations in relational algebra (Silberschatz, Korth, and Sudarshan, 2006). Barrier *le*s and *ler*s define a subnetwork of the argument layout's *le* network. Barriers are not passable when whole space connectivity is determined.

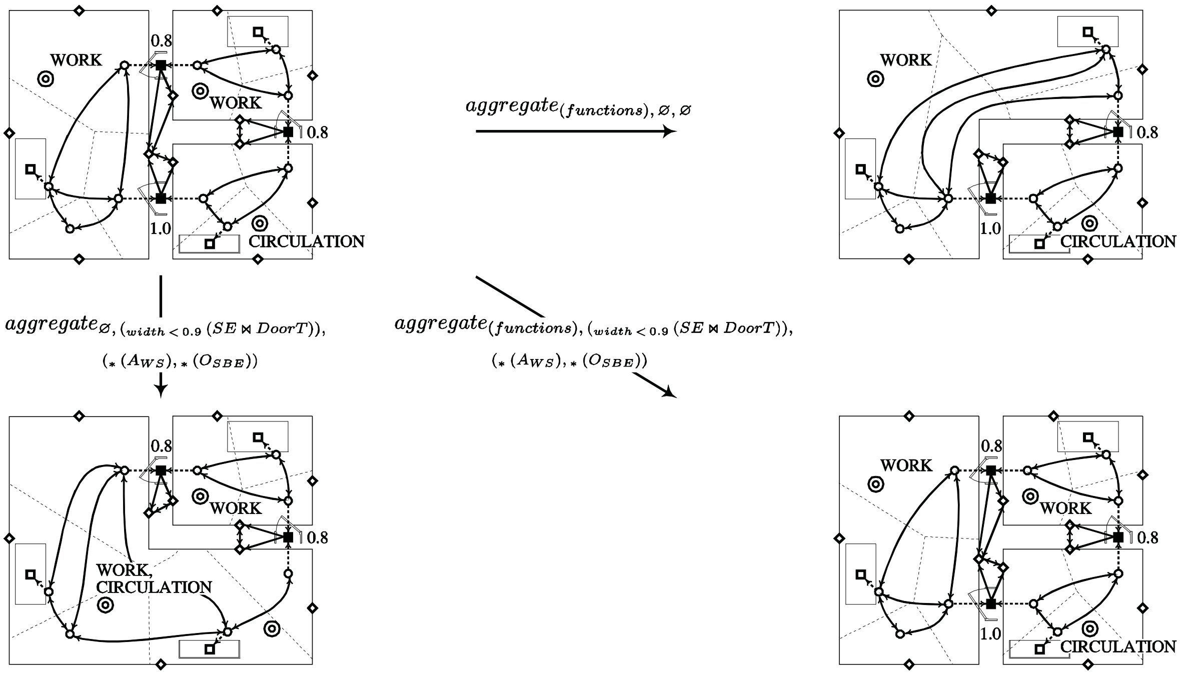

Fig. 4: Examples of the aggregate operation. A_{WS}, $B_{SBE,WS}$, and $B_{SBE,SS}$ relations are not shown.

Operation processing involves these steps:

1. The set of whole spaces *WS* in the argument layout *E* is partitioned into whole space subsets $\{WS_1 \subset WS, WS_2 \subset WS, \dots WS_n \subset WS\}$ such that all whole spaces in a subset WS_i belong to the same whole space group and are connected. Moreover, no two whole spaces in different subsets belong to the same group and are connected. Whole space groups are determined based on whole space attributes (as specified by G_{WS}). Whole space connectivity is determined based on the argument layout's *le* subnetwork (as specified by P_{LE_b} and P_{LER_b}). Directions of *ler*s are ignored to determine whole space connectivity.
2. Whole spaces in a subset WS_i with more than one whole space are replaced by a new whole space *ws*. The volume of *ws* equals the union of the volumes of the whole spaces in WS_i. Certain attribute values of whole spaces in WS_i (such as area or volume) are aggregated and assigned to *ws* attributes.
3. The intermediate layout is refined into the result layout (Section 2.2).

Examples of the *aggregate* operation are shown in Fig. 4. In the first example (Fig. 4, top right), grouping of whole spaces in the argument layout (Fig. 4, top left) is done based on the functions attribute. Since no barriers are defined ($P_{LE_b} = \emptyset$ and $P_{LER_b} = \emptyset$), the full *le* network of the argument layout is used to determine whole space connectivity.

In the second example (Fig. 4, down left), aggregation is done only based on whole space connectivity as no whole space attributes are specified ($G_{WS} = \emptyset$). Since A_{WS} and O_{SBE} elements are barriers, feasible paths between whole spaces include doors. Moreover, doors in these paths are more than 0.9 m wide. The new whole space has *WORK* and *CIRCULATION* functions.

In the third example (Fig. 4, down right), grouping is done based on the whole space functions attribute, but tracing of the argument layout's *le* network to determine whole space connectivity is restricted as in the second example. No whole spaces are aggregated because no pair of whole spaces belong to the same whole space group and are connected when barriers are considered.

3.4 *Decompose* operation

The *decompose* operation replaces whole spaces in the argument layout *E* that contain selected subspaces with smaller whole spaces. The volumes of the smaller whole spaces are derived from the volumes of replaced whole spaces and the positions of selected subspaces. For example, the *decompose* operation may be used to derive a layout from an argument layout where subspaces that surround luminaires are used to derive smaller whole spaces. The operation has the signature

$$decompose_{p_{SS}}(E)$$

where

- p_{SS} is a predicate on attributes of subspaces in *E* – targeted subspaces are used to decompose whole spaces, and
- *E* is a layout (a layout operation expression).

Any subspace is selectable for decomposition regardless of its volume type (Section 2.1). The positions of selected subspaces and containing whole space volumes are used to derive geodesic Voronoi cells (Aurenhammer and Klein, 2000, Section 2.1). These cells become the volumes of new whole spaces. Operation processing involves these steps:

1. A relational algebra selection operation is created and executed based on p_{SS} to select subspaces from the argument layout *E* that are used to derive new whole spaces.
2. For each whole space *ws* that contains a set of selected subspaces, positions of subspaces in and the *ws* volume are used as, respectively, sites and obstructions to generate geodesic Voronoi cells (Aurenhammer and Klein, 2000).
3. A whole space is created for each selected subspace *ss*. The geodesic Voronoi cell derived for *ss* in the previous step becomes the volume of the new whole space. Attribute values are copied from the whole space that contains *ss* or recomputed.
4. Whole spaces that contain selected subspaces are removed.
5. The intermediate layout is refined into the result layout (Section 2.2).

Examples of the *decompose* operation are shown in Fig. 5. In the first example (Fig. 5, top right), the whole space in the argument layout (Fig. 5, top left) is decomposed based on subspaces that surround luminaires. The weight of these subspaces is 2 or 3. Consequently, each whole space in the result layout contains a luminaire.

In the second example (Fig. 5, down left), the whole space is decomposed based on subspaces that surround luminaires and are near windows. The weight of these subspaces is 2. Each whole space in the result layout contains two luminaires. Decomposition based on subspaces that are distant from windows (whose weight is 3) would result in the same layout.

In the third example (Fig. 5, down right), the whole space is decomposed based on subspaces that surround windows and whose weight is 1. All luminaires in a new whole space are nearer (by Euclidean distance) to the position of the subspace that surrounds the window in the same whole space than to the position of the same kind of subspace in the other whole space.

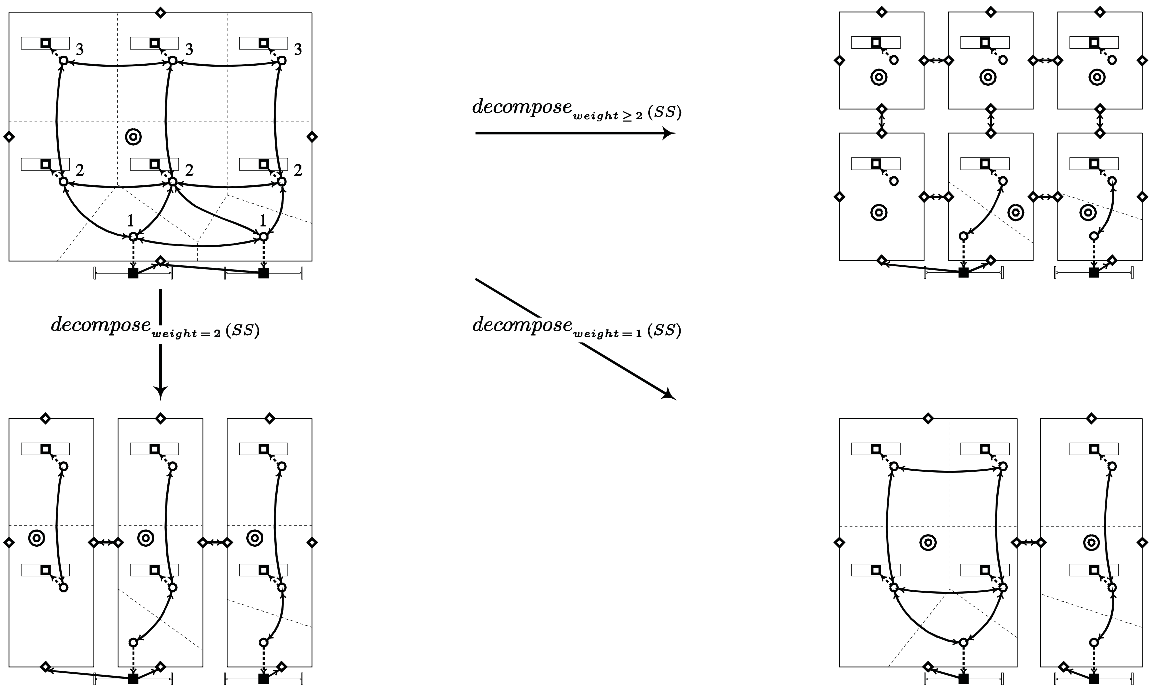

Fig. 5: Examples of the decompose operation. A_{WS}, $B_{SBE,WS}$, and $B_{SBE,SS}$ relations are not shown.

3.5 *Update*$_{WEIGHT}$ operation

The *update*$_{WEIGHT}$ operation derives weights of shortest paths from selected source *le*s to selected destination *le*s in an argument layout E and assigns these weights to the weight attributes of source *le*s. For example, the *update*$_{WEIGHT}$ operation may be used to derive a layout from an argument layout where luminaire weights reflect the weights of shortest paths to nearest windows. The operation has the signature

$$update_{WEIGHT, P_{LE_s}, P_{LE_d}, P_{LE_b}, P_{LER_b}}(E)$$

where

- $P_{LE_s} = (p_1(LE_1), p_2(LE_2), \ldots, p_k(LE_k))$ is a list of predicates on attributes of *le*s in E – targeted *le*s are used as source *le*s whose weights are updated,
- $P_{LE_d} = (p_1(LE_1), p_2(LE_2), \ldots, p_l(LE_l))$ is a list of predicates on attributes of *le*s in E – targeted *le*s are used as destination *le*s,
- $P_{LE_b} = (p_1(LE_1), p_2(LE_2), \ldots, p_m(LE_m))$ is a list of predicates on attributes of *le*s in E – targeted *le*s are used as barriers,

- $P_{LER_b} = \left(p_1(LER_1), p_2(LER_2), \ldots, p_n(LER_n) \right)$ is a list of predicates on attributes of *ler*s in *E* – targeted *ler*s are used as barriers, and
- *E* is a layout (a layout operation expression).

Only weights of source *le*s targeted by are updated by the operation. If there are multiple destination *le*s, then the weight of the shortest path from a source *le* to its nearest destination *le* is determined. The weight of a source *le* which is also a destination *le* is 0. Operation processing involves these steps:

1. A relational algebra selection operation is created and executed for each $p_i(LE_i)$ in P_{LE_s} to determine source *le*s (le_s) in the argument layout *E*.
2. Similarly, destination *le*s (le_d) are determined based on P_{LE_d}.
3. The nearest le_d is determined for each le_s. Search for the nearest le_d is restricted to a subnetwork of the argument layout's *le* network, as specified by le_bs and ler_bs. Only *ler* weights are considered to determine path weights. *Le* weights and *ler* directions are ignored.
4. For each le_s, the weight of the shortest path to its nearest le_d is assigned to its weight attribute.

Examples of the $update_{WEIGHT}$ operation are shown in Fig. 6. For all examples, *ler* weights are 1. In the first example (Fig. 6, top right), the weight of each subspace in the argument layout (Fig. 6, top left) is updated based on the weight of the shortest path to the nearest window. $B_{SBE,SS}$ elements are barriers for computing shortest paths. Luminaire subspaces with a weight of 2 are closer to the windows than those with a weight of 3.

In the second example (Fig. 6, down left), the weight of each space element is updated based on the weight of the shortest path to a destination luminaire (). $B_{SBE,SS}$ and $N_{SE,SBE}$ elements are barriers for computing shortest paths. Weights suggest that the right window is closer to the destination luminaire than the left one.

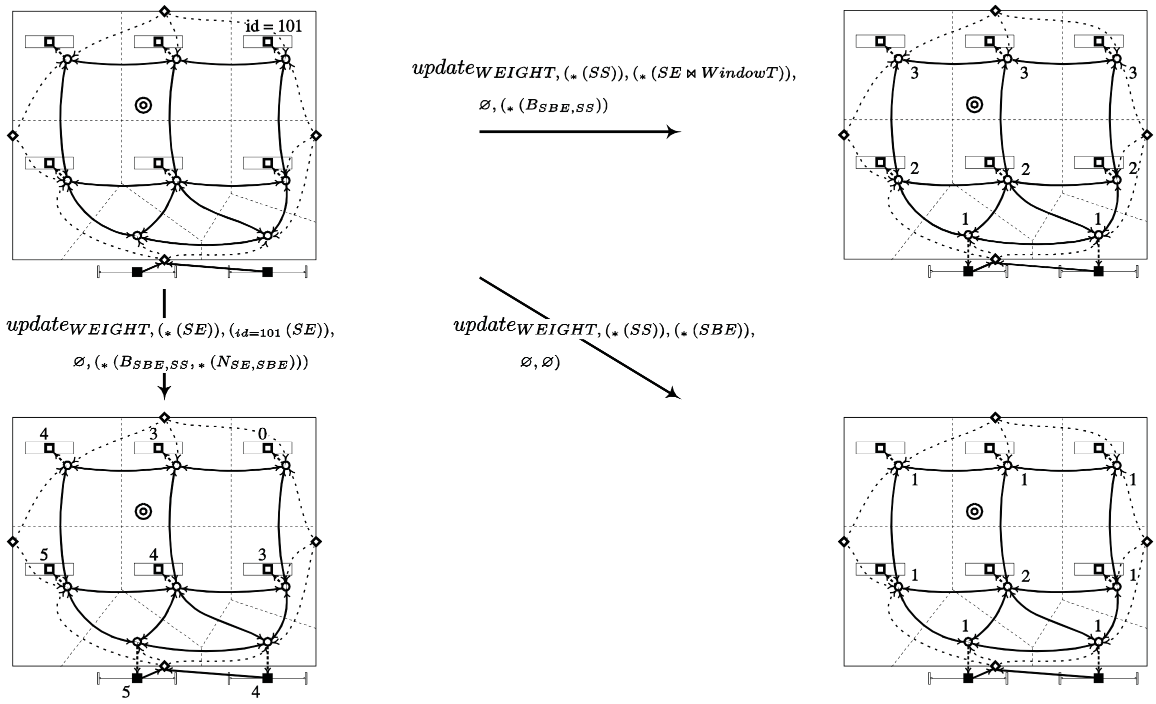

Fig. 6: Examples of the update$_{WEIGHT}$ operation. The $B_{SBE,WS}$ relation is not shown.

In the third example (Fig. 6, down right), the weight of each subspace is updated based on the weight of the shortest path to the nearest *sbe*. The full *le* network is used to compute shortest paths as no barriers are specified ($P_{LE_b} = \emptyset$ and $P_{LER_b} = \emptyset$). There is a luminaire subspace with a weight of 2 which is completely unbounded.

4. Example of a Layout Operation Expression

Layout operations may be composed into expressions. This is illustrated with an example in which a lighting-specific layout is derived from an existing layout *L* (Fig. 7). *L* includes walls, doors, windows, desks, and luminaires (Fig. 7, top left). The lighting layout derived from *L* includes luminaires and windows (Fig. 7, down right). While the L-shaped whole space in the lighting layout is enclosed by windows, the rectangular whole space is not. This information could be useful e.g. for a lighting controller to dim luminaires according to daylight availability. The expression uses the four layout operations defined in Section 3:

$$aggregate_{(weight),\ \emptyset,\ \emptyset}($$
$$update_{WEIGHT,(\ _*(WS)),\ (\ _*(SE\bowtie WindowT)),\ \emptyset,\ \emptyset}($$
$$decompose_{\ _*(SS)}($$
$$select_{(\ _*(WS)),\ \ _*(SE\bowtie LuminaireT),\ \ _*(SE\bowtie WindowT))}(L)$$
$$)))$$

Each operation modifies the layout resulting from the previous operation (respectively, *L* in case of the *select* operation):

1. Whole spaces, luminaires, and windows are selected from *L* (*select* operation).

2. Subspaces that surround luminaires in the layout resulting from step 1 are used to decompose whole spaces (*decompose* operation).
3. The weights of whole spaces in the layout resulting from step 2 are updated with weights of shortest paths to nearest windows (*update*$_{WEIGHT}$ operation). The full *le* network is used to determine shortest paths ($P_{LE_b} = \emptyset$ and $P_{LER_b} = \emptyset$).
4. Whole spaces in the layout resulting from step 3 are aggregated by their weights (*aggregate* operation). The full *le* network is used to determine whole space connectivity ($P_{LE_b} = \emptyset$ and $P_{LER_b} = \emptyset$).

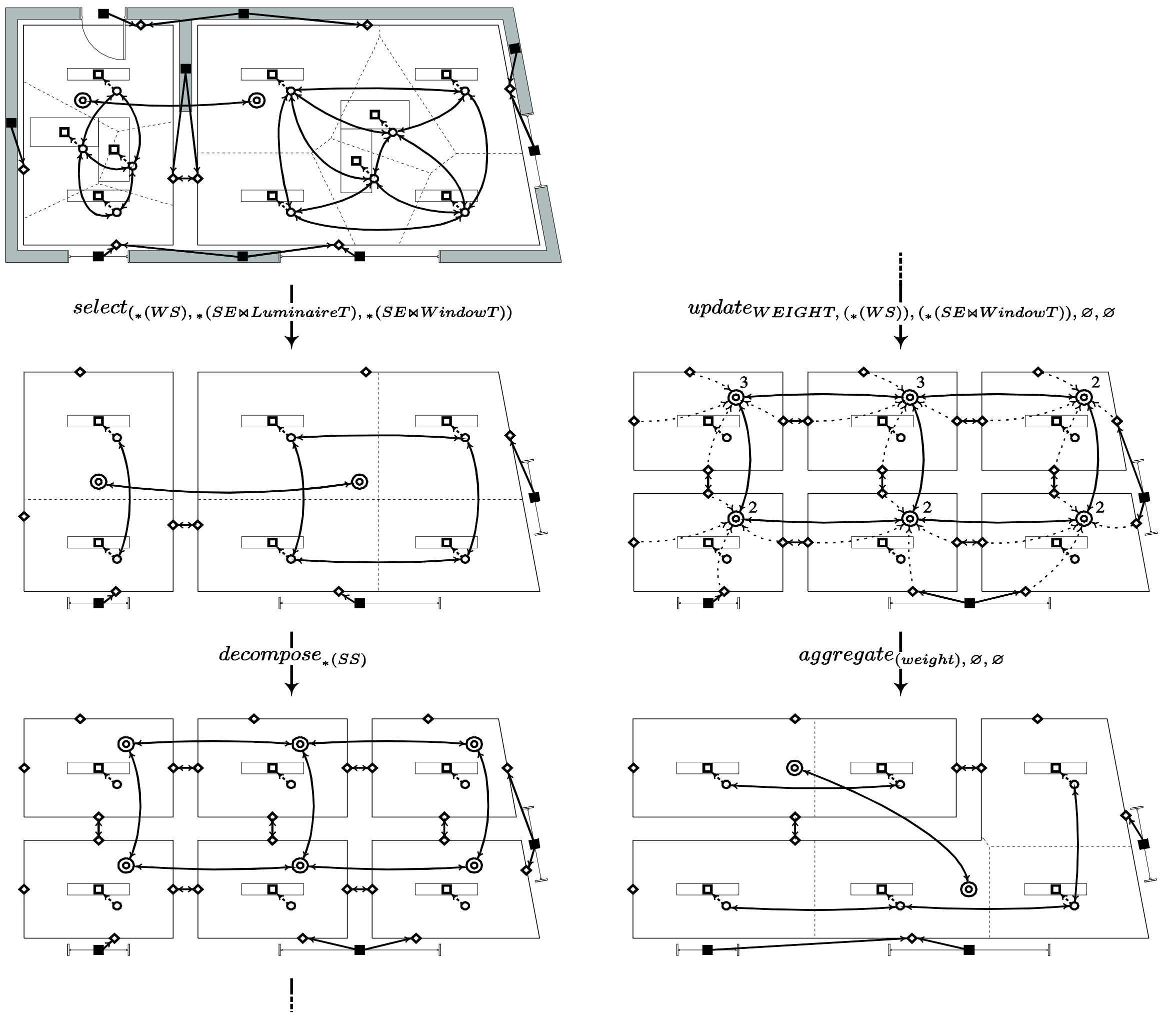

Fig. 7: Layout operation expression example. $B_{SBE,WS}$ and $B_{SBE,SS}$ relations (respectively, the $B_{SBE,SS}$ relation in the layout middle right) are not shown.

5. Conclusion

Operations on network-based space layouts have been introduced that are closed and may be composed into operation expressions. Variants of the proposed operations and additional operations may be defined to enhance the expressiveness of an emerging layout algebra. Binary layout operations are conceivable, including *union*, *intersection*, and *difference* operations. Similarly, there may be operations that relate *le*s in different layouts. For example, whole spaces in two layouts may be related by containment. With a rich set of layout operations, it may be feasible to define multiple, domain-specific space views of buildings (Rosenman and Gero, 1996) in a compact manner and to apply those views to individual buildings. Certain views may be sufficiently generic for reuse across buildings.

Acknowledgement

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IMMERSIVE REMOTE CONSTRUCTION SITE MONITORING USING LIVE AUGMENTED PANORAMAS

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ABSTRACT: *In this project, we have proposed, developed and tested a system for remote building site monitoring based on 360° panoramas. The system, that consists of a computer, a remote network Pan-Tilt-Zoom (PTZ) camera installed on site, a pair of goggles and an orientation sensor, starts by capturing images of the site in all orientations, then assembles them into a static 360° panorama. The panorama can then be remotely viewed in an immersive way by a user wearing goggles equipped with an orientation sensor. In addition, the panorama is augmented with a live video stream that is overlapped and registered at its corresponding location in real time within the panorama as the camera moves. Finally, the panorama is further augmented with a 3D model of the building being built. Results show that the use of a panorama as a background for visualizing the video stream offers a spatial context to the video data, enabling the user to better understand the scene and more freely view the environment. Moreover, the use of goggle-based head tracking panorama visualization enhances the feeling of immersion with respect to a PTZ camera alone, as users get a much better feeling of remote presence than when viewing the stream on a standard monitor. The addition of live video synchronized with the panorama further enhances the experience, giving users the feeling that the scene is not only immersive but also alive. Finally, the added bonus of panorama augmentation is considered very positive, especially because the model pose does not need to be updated after initialization, giving the illusion of a perfectly stable tracking. Because of its accuracy, panorama-based augmentation appears to have a lot of potential for building site monitoring applications.*

KEYWORDS: *Panorama, augmented reality, construction, monitoring, telepresence.*

1. Introduction

Building site monitoring can be a time-consuming task requiring specialized and thorough understanding of the construction project, and careful observation attentive to detail. On-site monitoring tasks may include comparing the drawings with the building (to verify the work is done according to design and on time), assistance (providing help to workers facing an unexpected situation), evaluating potential safety issues, etc. Those tasks require the user's presence on site because he needs to see the site in order to take observations/decisions/actions. However, on-site presence is not always possible for various reasons: construction sites may be far away or not easily accessible, users may be busy at their office, etc. Construction site monitoring takes time and involves costs. Solutions that would save users from having to visit the site by letting them do the monitoring remotely would contribute in saving time and lowering costs.

Phone-based video collaboration was proposed to remotely assist remote on-site users facing unexpected problems (Caron, 2009). In the solution he proposed, a user on site would use his phone to capture live video of a scene, that would then be broadcasted live to a remote user. The system was designed to run on the limited bandwidth of 3G wireless networks. Live video broadcast from smart phones is now commercially available (movino.org, qik.com. etc.), and could be used for that purpose. However, that solution is constrained by the necessity of having a user on site to hold the camera. Consequently, the remote user only has limited control on the camera orientation, and has to ask his colleague to turn around to let him view other areas, because phone cameras have a limited field of view. Fixed cameras do not require anyone to hold the camera, but suffer from the same field of view limitation and are also constrained by a single point of view.

Pan/Tilt/Zoom (PTZ) cameras are often used to overcome the limited field of view of video cameras, by allowing users to remotely explore the entire 360° environment. However, when displayed on a computer monitor, the sweeping camera video stream does not give the user a true sense of presence. First, while the user can remotely control the camera orientation, the monitor on which the stream is displayed does not rotate accordingly around the user, giving the user no physical cue on the true instantaneous camera orientation. Also, by changing the camera's focal length (zoom in/out), the user also changes the camera's field of view, altering his perception of size, distance and orientation. Controlling the camera can be particularly important for building site monitoring, where several events may occur in various locations, and where a limited field of view, combined with altered perception of the environment may limit the user's capacity to understand the scene and events.

Several PTZ camera models can rotate around 360°, and therefore capture images of the whole surrounding environment. Images captured by such cameras can therefore be stitched together to form omni-directional panoramas (Szeliski, 2010). Panoramas are now increasingly popular and are used in mirror worlds such as Google StreetView. They offer an immersive representation of reality, giving the user a better impression that he is actually on site. However, the feeling of immersion is limited by the standard 2D monitors that are used to view those panoramas. In spite of the fact that a panorama covers the entire environment, browsing it on a standard monitor is more similar to watching a movie than to feeling truly on-site. Panoramas also have been viewed on more visually immersive devices, such as CAVEs (Lee et al., 2011).

Augmented reality (AR) can be a powerful tool to help users understand the scene captured by a video camera. De Haan et. al. (2009) showed that by superposing a 3D model to surveillance camera video streams, users could more easily understand the 3D structure of the environment. AR could also be used to make the comparison between the model and the building easier (Woodward *et al.*, 2010), by overlaying the model to reality. However, AR is not easy to achieve. To get accurate superposition between a model and reality in 6 degrees of freedom (DOF), the exact camera pose (position and orientation) must be known. While orientation can be measured at a relatively good accuracy using orientation sensors, measuring position is challenging in non-controlled outdoor environments (Azuma, 2001) such as building sites. Therefore, augmenting images from a fixed position PTZ camera would simplify the problem dramatically, as the tracking problem would go from 6 DOF (position and orientation) to 3 (orientation only). In the work presented by Kähkönen et al. (2007), a set of fixed web cameras installed at various locations are used for stable augmentation.

In this project, we propose the use of a single PTZ camera for remote building site monitoring. Through a fusion of live video, 360° panoramas and augmented reality, our system provides the user with an immersive augmented live video experience. By providing a context to the video stream, it enables the user to get a better perception of the scene, in addition to providing tools for more efficient monitoring.

2. Method

2.1 Hardware Setup

Our system consists of a PTZ camera installed on a building site (see Figure 1). The camera is connected to a network. A computer, connected to the same network, can remotely access the camera images and control its orientation and focal length. A pair of goggles equipped with an orientation sensor is connected to the computer. In our setup, we used an Axis 213 PTZ Network Camera, a standard double-core desktop computer running Windows XP, a Vuzix IWear VR920, and a miniAHRS orientation sensor from Innalabs.

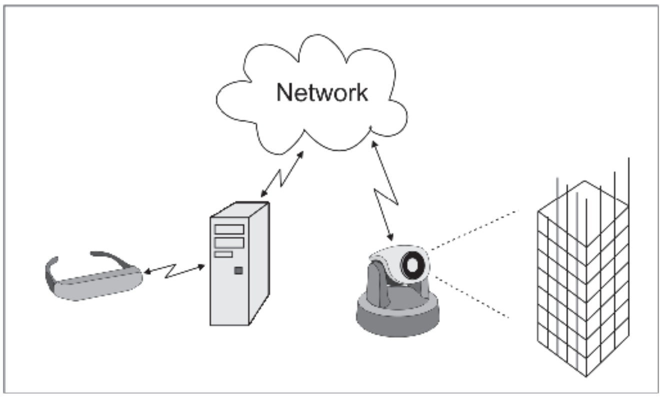

Fig. 1: Layout of the proposed system: goggles, computer, network, camera, and building site.

2.2 Software Operation

The computer runs a program that is used for various parts of the operation of the prototype.

2.2.1 Panorama Creation

The program first sends a series of commands to the camera, to capture images in all orientations. The purpose of this is to create a 360° panorama. The program calculates efficient coverage to provide an overlay of about 50% between images while minimizing the number of images required to cover the entire 360°. The images are then stitched together to form the panorama. For that purpose, we used Microsoft ICE. ICE is designed to create panoramas by automatically matching and stitching images. However, that process is prone to error for various reasons (for instance because image features used for matching are different and not distributed uniformly). To maximize the chance of obtaining an accurate panorama, we feed MS ICE with the orientation in which each image as been captured, the orientation data being provided by our image capture program. Therefore, ICE is only used to perform image blending and to store the resulting panorama as a jpeg image. The resulting image is then loaded in the visualization program. Using a standard single core desktop computer and the Axis camera, a typical scenario takes 2 minutes 43 seconds to capture the images, 1 minute 40 seconds to stitch them and 50 seconds to save the panorama.

The panorama that was created using the Axis camera covers 360° horizontally, but only about 115° vertically. That vertical limitation is due to the camera's mechanical characteristics, as it was designed as a ceiling camera. However that did not prevent our system from operating normally; our system can be used on cameras that can cover the entire 180° × 360° environment.

The system was also programmed to re-create the panorama periodically, to make sure it remains temporally coherent with the live video stream.

2.2.2 Panorama Visualization with Video Augmentation

By wearing the goggles, the user can view the panorama in all orientations. Since the goggles are equipped with an orientation sensor, the user can view the panorama in any orientation simply by rotating his head, as if he was on site, in a 3 degree-of-freedom visualization experience. Therefore, he feels visually immersed in the remote building site environment, and gets a better perception of the scene.

The panorama is a static image that is captured at the beginning of the visualization session. That means the visualization experience is on a static image. But the program also augments the panorama with a live video stream captured by the camera. The stream is overlaid inside the panorama, in the region that corresponds to the actual field of view of the camera. This is illustrated in Figure 2, where a simulated moving video stream is overlaid onto an equirectangular panoramic projection at 3 different locations over its path. The streams were highlighted in red for clarity. Using this technique, a portion of the panorama is periodically overlaid by a live stream, making it "alive". To synchronize the live video stream with the panorama, we simply used the instantaneous orientation values returned by the camera.

The orientation of the camera can be controlled in 2 ways. The first method, called "head tracking mode", is a direct mapping of the user's head orientation. In that mode, the remote camera reproduces the user's head movements. Therefore, when the user turns his head to view a different portion of the panorama, the static panorama view is rotated based on the user's new head orientation, and a rotation command is also sent to the remote camera. This ensures that the user can always get a live video update in the direction he is looking at. The user can also zoom-in his view of the static panorama, or get the remote camera to zoom-in optically, or both simultaneously, to get a more accurate display of some portions of the remote environment.

The second camera control method, called "surveillance mode", is a constant sweep back and forth between user-selected orientations. In that mode, the system is programmed to send rotate commands to the camera to periodically sweep between predefined orientations. During that time, the user can still look in any orientation in the panorama without interfering with the camera operation.

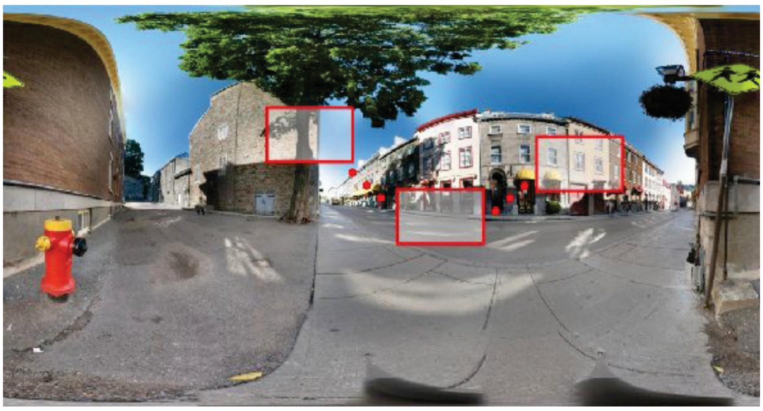

Fig. 2: Panorama with overlaid video stream, following the camera orientation.

2.2.3 Panorama visualization with model augmentation

In addition to being augmented with live video, the panorama is further augmented with a 3D model of the building being built. The model is anchored to the panorama using a method described in Poirier (2011). From then on, it is always displayed with the same orientation with respect to the panorama, providing a virtually perfect tracking and jitter-free augmented visualization experience.

In parallel, a markup tool allows users to augment the panorama with hand drawings and notes, that can also be attached to a certain moment in time, enabling online or offline multi-user immersive collaborative construction site monitoring.

2.2.4 Temporal panorama visualization

The system also provides the option of recording the panorama and the video stream. Therefore, the augmented panorama with live video can be "played back" using the same visualization technique: the user can view the panorama in any orientation while the video stream, displayed at the corresponding location in the panorama, can be played forward, backward, at normal or accelerated speed, and with of course the ability to begin at, or jump to, any specific moment in time. This provides the user a tool to navigate the panorama in 4 degrees of freedom: orientation + time.

3. Results and Discussion

3.1 Initial tests

3.1.1 Surveillance mode

The method was first tested on the roof of a building in the city of Québec. The goal of that first experiment was to test several features of the prototype. It was run during a whole day in surveillance mode, and recorded the stream at the same time. The prototype was then used to view the panorama with pre-recorded video registered to the panorama. We could browse the panorama temporally, going back and forth in time, and at the same time explore the panorama in 3 degrees of freedom.

A basic model of the building was also overlaid to the panorama. This is illustrated in Figure 3, where the model (red) and the video stream (artificially brightened for clarity) are both overlaid onto the panorama. When the video stream covered model-augmented areas, the model was overlaid on top of the live video stream, which was overlaid on top of the panorama. By moving the area of live video (behind) a model area, and then moving it away, and then back, or alternatively by turning on and off the augmentation model, the video can easily be compared to the designed model. This augmentation test confirmed that the model can this way be easily compared with the real building: the model elements are directly overlaid on top of their corresponding element of the real building, making visual comparisons easy.

Fig. 3: 3D building model overlaid onto live video, both overlaid onto panorama.

It should be noted that unlike many other augmented reality applications, this prototype showed no model jitter relative to the real world. Once anchored to the panorama, the model is perfectly stable, as it is attached to a static image. Augmenting the world from panoramas might be seen as a major constraint in the AR world, as it forces visualization to be done from fixed positions. However, it also has advantages. Building site monitoring may require accuracy: the verification as to whether a given wall or post has been installed at the right location has to be done with precision, as the decision that will arise may have major consequences. Therefore, an augmented reality system designed for engineering should be highly accurate to support those decisions. Jitter free augmentation is therefore necessary, and the fixed position constraint that is required to achieve it may seem minor when compared with the resulting augmentation quality. In that context, in the context of building site monitoring, fixed-position panorama-based augmented reality appears to be, at this time, a mode of augmentation that is preferable to 6 DOF augmented reality because of the accuracy of its augmentation, something that is very hard to obtain from 6 DOF tracking systems.

However, some error was observed in the overlay of the video stream. There are 2 probable reasons: low quality panorama assembly, and low precision camera orientation. Both types of errors can be observed in Figure 4. On the top right of figure 4, panorama assembly error is visible on the electric cable. Video overlay error is also visible on top of the overlay, near its center: the light pole is broken at the edge of the stream. Video overlay error caused artificial jittering, which, when overlaid in a region also overlaid by the model, could be wrongly interpreted locally as model jittering or misalignment.

Panorama assembly error could be explained by various factors:

- The projection plane of the camera is not centered with the rotation axis of the camera, causing parallax error, and therefore causing panorama anomalies.
- The panorama assembly method, solely based on orientation data provided by our program:we have observed that the camera often points in a slightly different direction than the direction indicated by our program (Bilodeau, 2010).
- The quality of the camera calibration, which was done using the GML Camera Calibration Toolbox (Latulippe, 2010).

***Fig. 4:** Zoomed view of the video overlay, showing both panorama and overlay errors (circled).*

3.1.2 Head tracking mode

The method was then tested on another side (the rear) of the same building, this time in head tracking mode. Five different users tested the system in an informal evaluation. Qualitative results have shown that the use of goggle-based head tracking panorama visualization dramatically enhances the feeling of immersion with respect to a PTZ camera alone. Users said they got a much better feeling of remote presence than when viewing the stream on a standard monitor, for 2 reasons: first, because the use of goggles equipped with an orientation tracker frees the user from having to browse the image with a mouse, and second, the 1:1 relationship between head orientation and panorama view makes it feel as if they are actually on site. Users did complain about the limited display width of the goggles (32°, compared with about 180° for the human eyes). However, that did not prevent them from seeing the entire panorama; it just constrained their instantaneous field of view. That did not prevent them from feeling immersed, either. The addition of live video synchronized with the panorama further enhanced their experience, giving them the feeling that the scene is not only immersive but also alive. That was quite visible when viewing vehicles or pedestrians crossing the panorama-video edge.

3.2 Construction site

Currently, the method is being tested in a demonstration project, in England, for evaluating its potential for monitoring the progress of a (real) construction site, of a motorway bridge. Two Bosch AutoDome cameras have been installed, each on top of a pole along the highway. The cameras were used to create panoramas, on top of which live video streams of the site are overlaid, as well as the model of the bridge being built. Our objective is to evaluate the potential of the tool in an operational context.

The project is currently under development, and our prototype is being tested on those cameras. Visual observation of the images sent by the cameras shows that the pole is periodically drifted by the wind caused by the vehicles passing by, causing camera movement, and therefore image blur, especially with increasing focal length values. Consequently, this has an effect on the assembly of the panorama, as well as on the accuracy of the video overlay, the image being often off by a few degrees. That decreases the accuracy of the system, but still allows users to see what happens on site in the context of the panorama and of the bridge and road models. Another issue is that the cameras can rotate in any orientation. Since they are installed along the motorway, they can target several private properties in the neighborhood. Although viewing those properties is important for panorama assembly and 3D model overlay, they are not required for site visualization and have to be protected. A masking process is therefore being implemented for that purpose.

4. Conclusion

In this experiment, we proposed, developed, and tested a prototype system for immersive remote building site monitoring based on the use of 360° panoramas. The system starts by building a 360° panorama of the environment, then overlays a live video stream at the corresponding location. The user can then view the augmented panorama using a pair of goggles equipped with an orientation sensor that display the panorama through an immersive visualization experience. The system can also overlay a 3D model of the building to the panorama to make the monitoring process easier. The system was tested on simple cases, and during an informal experiment, a small group of users confirmed that the system was immersive and made it easier to understand the site compared to just browsing the panorama on a monitor using a mouse.

The use of a panorama as a background for visualizing the video stream has a major advantage over standard video visualization: it provides a spatial context to the video data. The user's view is not limited by the narrow field-of-view video stream, but he can view the whole environment in which it is located, enabling him to better understand the environment and context, and more easily interpret and localize the events occurring on site.

Finally, the added bonus of model augmentation is considered very positive, as it enables an easy comparison between the model and the building. Moreover, since augmentation is done on a static panorama, the model pose needs to be calculated only once, giving the illusion of a perfectly stable tracking. The use of a panorama for augmentation would normally be seen as a major constraint for portable augmented reality applications, as it requires the visualization to be done from a fixed position. However, it turns out to be a very good solution for building site monitoring applications, for which accurate augmentation is important.

5. Future Work

The use of panoramas can be seen as a constraint for monitoring a building site, as panoramas are static images and things may change quickly on a site during the day. Therefore, someone using the system but looking at a portion of the panorama that does not contain the live video stream may actually be looking at an outdated image. We have made our prototype capable of automatically re-generating its panorama, but that process takes some time, and during that time the camera cannot be used for other purposes. One solution would be to constantly update the panorama with each image captured by the live camera: each frame captured by the camera could, in addition to being overlaid to the panorama, be stamped into it. That would constantly update the panorama, and decrease the chance of the user seeing outdated data.

Our current implementation of the video augmentation relies on the instantaneous camera orientation data provided by the camera itself. Since the motorized orientation system of the camera we used is not precise, an offset could often be seen between the video and the background panorama. To alleviate this problem, one solution would be to fine-tune the location of the video overlay using image matching technology. This would ensure the live stream is overlaid exactly to the panorama, minimizing the offset.

In addition to augmenting the panorama with a model, we could also augment it with other data, such as sensor readings (e.g. temperature measured on site, sound, etc.), making the monitoring experience more complete.

The system does not have to be limited to 1 panorama – we could easily envision several panoramas obtained by a number of cameras on a site, and the remote user could navigate between those augmented panoramas.

Finally, the camera could be controlled to detect changes in the scene, and the system would automatically update the panorama for those areas that have changed. Similarly, it could increase the camera's focal length to increase panorama resolution for those areas that require more detail.

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GREEN BUILDING INFORMATION MODLING… WHAT'S NEW?

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ABSTRACT: *Building Information Modeling (BIM) as a powerful set of design management's tool has been highlighted by the Architecture, Engineering, and Construction (AEC) industry. BIM has significant advantages over the entire building lifecycle, particularly design but also construction and facility management. The full impact of BIM on the evolution of design tools in the AEC industry has recently become a topical research area. Also, Sustainable Design has become another buzz word in the construction industry. With so many ideas and descriptions circulating, it's important to define what sustainable design is and how this process and Building Information Modeling (BIM) work together. Sustainability is a relationship, or balancing act, between the triple bottom line: the environmental, economic and community impacts. Our definition of sustainable design is achieved when we can positively affect all three areas. Building Information Modeling (BIM) tools provide thorough information to guide and improve design solutions. So, the aim of this paper is to introduce a new vision towards clear methodology of Interactive link between BIM (Building Information Modeling) and Sustainable Design and construction. This Interactive link termed renamed Green Building Information Modeling.*

KEYWORDS: *Building Information Modeling "BIM", Architecture, Engineering, and Construction "AEC" industry, Sustainable Design, Green BIM..*

1. Introduction

For most people, the environmental impact of buildings is startling. Sustainable design seeks to mitigate this negative impact through the use of environmentally sensitive design and construction practices. The goal of sustainable design is to produce green buildings that are "environmentally responsible, profitable and healthy places to live and work", (U.S. Green Building Council, 2004). In a perfect world, energy simulations and design tools would be so well integrated that each time an architect moved a wall, added a window, or changed a lighting specification, the building's predicted energy performance would be updated and displayed instantly. With that sort of real-time feedback, designers would quickly become skilled at optimizing the energy performance of their designs, and new buildings would be rapidly approaching carbon neutrality, (Leicht R. M. & others, 2007). Along the way, other aspects of a building, such as how well it uses daylight, how procuring its material will affect the planet, and even how much it will cost to build, could be similarly tracked and optimized. And all of this would be done while sharing a design seamlessly across disciplines. BIM is an approach to building design involving the use of a digital building model created from coordinated, consistent design information enabling whole-building analysis, faster decision-making, and better documentation.

That world has not yet arrived, and the path to it is strewn with obstacles. But in some settings it is becoming so close, thanks to the convergence of data-rich, three-dimensional (3D) design tools, ever-faster computers, and accepted protocols for sharing digital information about buildings across platforms. In spite of the significant investment that designers, construction engineers and contractors have to make to adopt building information modeling (BIM), they are flocking to it because it can reduce errors, streamline costs, and improve the performance of a facility in dozens of ways, not least of which is green performance. As the number of designers working in BIM grows, so does the opportunity for using those virtual models to do more than just estimate costs and to create an environmentally sensitive design. With the advent of BIM, however, "technology is facilitating a much bigger movement around sustainability in the buildings space," Bhatt added. Energy modelers use specialized software to create a virtual model of a building. They then subject that model to the building's anticipated weather and usage patterns to predict its heating and cooling loads and energy use. Until now, setting up an energy model took many hours, even for a relatively simple building, so iterations through various design alternatives were slow and expensive.

2. Building Information Modelling

BIM is not just software but a methodology of practice. BIM is described as: "a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward, (Magdy I., Robert K., George S., 2004). So, Building information modeling is an innovative new approach to building design, construction, and management.

BIM is a new approach of "Virtual Building Construction" based on parametric CAD technology. It is a building design and documentation methodology that significantly improves building design practice and makes the construction process easier and faster for everyone involved. It allows all of the graphical and non- graphical building information for a construction project to be readily available by the use of relational databases that store, access, and retrieve all of the information about building components, (Bernstein P.G., and Pittman J.H., 2005). Also, (BIM) can be described as process of generating and managing building data during its life cycle. Typically it uses three-dimensional, real-time, dynamic building modeling software to increase productivity in building design, construction, and operation. BIM covers geometry, spatial relationships, light analysis, geographic information, quantities and properties of building components (for example manufacturers' details). Quantities and shared properties of materials can be extracted easily. Scopes of work can be isolated and defined.

2.1 BIM Today

After the models are developed and coordinated, the model will then become the as-built for the project. It will take some time for the design and construction team members to purchase the software, hardware and train their staff to be proficient in BIM and 3D coordination. The building owners will also need to invest in some of the same technology and provide training to their staff in maintaining the building model after the construction is complete, (Fischer M., and Kunz, J., 2006). As new technologies are developed and introduced to the industry, we will see the models interfacing and communicating with a cost data base extracted from the model (referred to as 5D). We will also see scheduling, planning and measurement of the progress of a construction project which will also be based on data extracted from the model (referred to as 4D). So there will be a major paradigm shift in the way we conduct business in the future, as a design professional, as a constructor, and as a building owner. BIM software offers many benefits for general building design. The best BIM software uses a centralized, parametric model allowing "live" viewing and automatic coordination of all plans, quantity takeoffs, and other related documentation. These integrated deliverables have explicit relationships with each other and the model, resulting in better-coordinated construction documents that minimize errors and omissions. The design model is used for a variety of building analyses, automatic clash detection, design visualizations, and precise quantity takeoffs. In addition, the resulting digital design model can be leveraged for a variety of related tasks, such as construction sequencing, digital fabrication, and facilities management.

The concept Building Information Modeling (BIM) may be described as the way, (Brown, F.E. & others,1995) (Popovas V. & others., 2003):

- To develop the strategy of building project, construction, and maintenance management based on the computer aided modeling and simulation technology of the project and its development processes;
- To ensure the integrated management of graphical and information data flows enabling to combine virtual graphics (CAD), (Brown F.E. & others, 1995). with information data basis and process descriptions, all this performing under a unified software environment;
- To transform individual executors into teams and decentralize tools into complex solutions, to integrate individual tasks into processes;
- To perform life cycle operations of a construction project faster, more effective, and with lower cost.

The interoperability requirements of construction documents include the drawings, procurement details, environmental conditions, submittal processes and other specifications for building quality. It is anticipated by proponents that BIM can be utilized to bridge the information loss associated with handing a project from design team, to construction team and to building owner/operator, by allowing each group to add to and reference back to all information they acquire during their period of contribution to the BIM model.

2.2 BIM Benefits

The key benefit of BIM is its accurate geometrical representation of the parts of a building in an integrated data environment (CRC Construction Innovation, 2007). Other related benefits are:

- *Faster and more effective processes* – information is more easily shared, can be value-added and reused, (Bazjanac, V., 2006).
- *Better design* – building proposals can be rigorously analyzed, simulations can be performed quickly and performance benchmarked, enabling improved and innovative solutions.
- *Controlled whole-life costs and environmental data* – environmental performance is more predictable, lifecycle costs are better understood.
- *Better production quality* – documentation output is flexible and exploits automation, (Associated General Contractors of America, 2005).
- *Automated assembly* – digital product data can be exploited in downstream processes and be used for manufacturing/assembling of structural systems, [See figure 1].
- *Better customer service* – proposals are better understood through accurate visualization.
- *Lifecycle data* – requirements, design, construction and operational information can be used in facilities management.

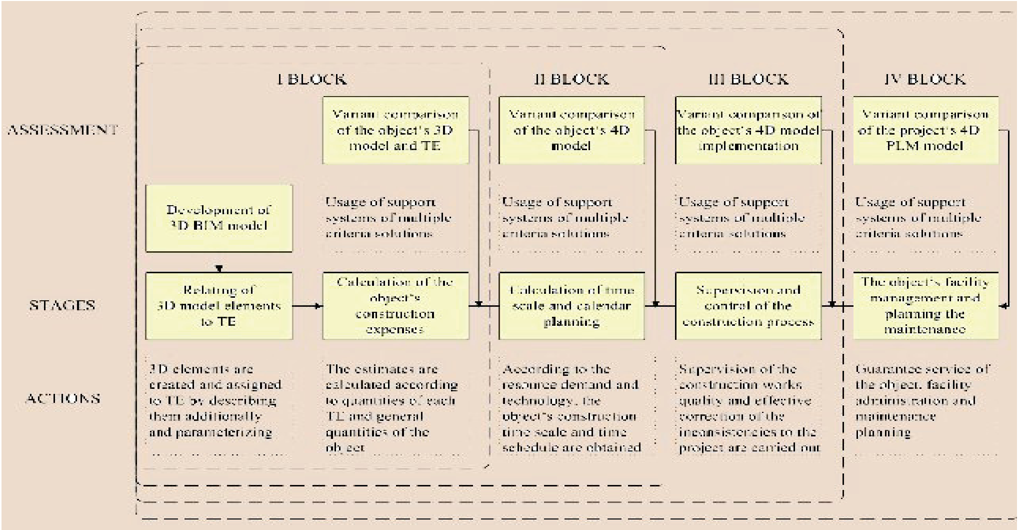


Fig. 1: Model of the construction project automated management within its entire life (Vladimir P. & others, 2006)

Stanford University Center for Integrated Facilities Engineering (CIFE) figures based on 32 major projects using BIM indicates benefits such as (CIFE, 2007):

- Up to 40% elimination of unbudgeted change.
- Cost estimation accuracy within 3%.
- Up to 80% reduction in time taken to generate a cost estimate.
- A savings of up to 10% of the contract value through clash detections.
- Up to 7% reduction in project time.

Building information modeling supports the continuous and immediate availability of project design scope, schedule, and cost information that is high quality, reliable, integrated, and fully coordinated. Among the many competitive advantages it confers are:

- Increased speed of delivery (time saved)
- Better coordination (fewer errors)
- Decreased costs (money saved)
- Greater productivity
- Higher-quality work
- New revenue and business opportunities

For each of the three major phases in the building lifecycle– design, construction, and management– building information modeling offers access to the following critical information:

- In the design phase– design, schedule, and budget information
- In the construction phase– quality, schedule, and cost information
- In the management phase– performance, utilization, and financial information

The ability to keep this information up to date and accessible in an integrated digital environment gives architects, engineers, builders, and owners a clear overall vision of their projects, as well as the ability to make better decisions faster– raising the quality and increasing the profitability of projects.

2.3 Future Models

With the new BIM based CAD packages available on market today, one can conclude that this is going to be the trend of the future, and that better capabilities would be eventually implemented to best describe the building model and to best fit the needs of the designer without sacrificing creativity and practicality (Ibrahim and Krawczyk 2003).

2.3.1 The integrated model:

An integrated model [See figure 2], expects that all the systems and required information to be integrated in one big CAD system that can answer all the questions and have all the information in one database. BIM as a concept supports to some extent this point of view, but it stops short of providing the whole related items in buildings. Architectural BIM systems deal only with architectural elements, making it difficult to coordinate such information as structural members' sizes after being analyzed and sized. Information about other objects such as windows and doors can be to some extent downloaded from vendors' web sites, although the current implementation does not keep this information linked to that source. This deficiency might prevent from getting the latest price for an up to date cost estimate, (Magdy I., Robert K., George S., 2004).

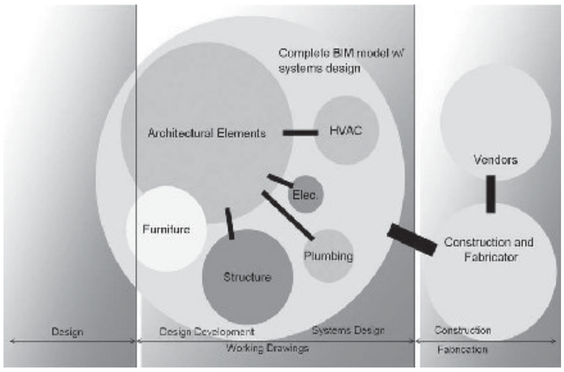


Fig. 2: The Integrated Model
(Magdy I., Robert K., George S., 2004)

2.3.2 The Distributed Model:

On the other hand, this model [See figure 3], expects that the architect building model would be a referential model. A model that can access and point to the information from where it is stored and make use of it but not imbed it in the CAD model, allowing other systems to access the same information and to make use of it in their own way.

Many specialized systems can communicate through one model. Every system does what it specialized in and passes the information to the next. This model can reach up to the construction site where the information ends its journey. The medium for sharing the information could become the Internet, (Magdy I., Robert K., George S., 2004).

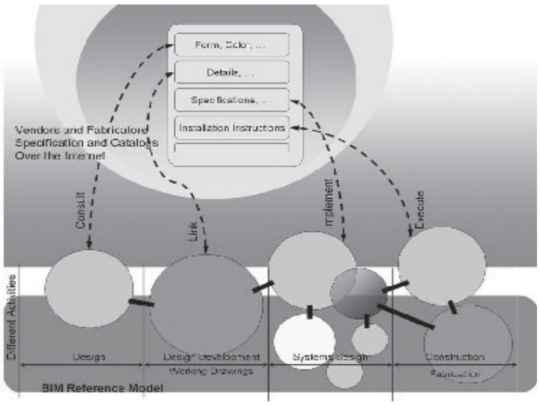


Fig. 3: The Distributed Model
(Magdy I., Robert K., George S., 2004)

3. Green Architecture

Sustainable, or green design, are buzzwords of contemporary architecture. For reasons that vary from meeting energy codes, managing increasing fuel costs, reducing waste, expression of personal values, or the desire for self-sufficiency, more people are thinking green. Internationally, the trend toward sustainable-building design also is strong. Governments around the globe are implementing new building regulations that mandate sustainable design. Many countries already require performance assessments to comply with building regulations. Although the building industry's (and owners') interest in sustainable design is undeniable, it has its challenges. Some issues are technical, while others relate to standard industry processes and practices. Cost always is a concern. However, the growing market demand for sustainable design is outweighing and overcoming these hurdles and driving fundamental process changes throughout the industry. Transformative concepts that facilitate sustainable design, such as integrated project delivery and BIM, quickly are becoming the standard.

3.1 Standards for Sustainable Design

Conservation efforts and sustainable design gained momentum during the 80s and 90s, as focus shifted from point strategies like solar heating to a holistic approach to green design. ***The LEED rating system awards points for satisfying*** specified green building criteria in five major categories: site design, indoor environmental quality, and efficient use of energy, materials, and water.

But what is the cost of sustainable design? Depending on the building project and the "green" measures selected, the net change in construction and operating costs can range from a savings to unaffordably expensive. Long-range lifecycle assessments may paint a rosier picture but in today's tight economy, building developers and owners are especially sensitive to the value that their design and construction dollar buys. Complicating the cost analysis, the design process can require more resources as many of the engineering and analysis tasks that used to be conducted later in the design process are shifted towards earlier phases to assist in evaluating sustainable design options, and others that may never have been done at all (such as day lighting studies) become routine.

BIM, supported by appropriate technology, has the potential to reduce the cost of sustainable design by making the information required for sustainable design, analysis and certification routinely available simply as a byproduct of the standard design process.

4. Green BIM: Sustainable Design with Building information Modeling

How can Building Information Modeling (BIM) help to design better "green buildings"? Perhaps the greatest advantage of BIM in sustainable building design is building analysis. Sustainable building design hinges on the ability to gain insight into a building's performance through design analysis and optimization. But evaluating building performance based on the building representations produced by conventional computer-aided-design (CAD) or object-CAD solutions requires a great deal of human intervention and interpretation and makes the analyses unduly time-consuming and costly. The thoughtful designer can use BIM models to save resources AND money for project owners by incorporating analytical studies into the early design phase. For most people, the environmental impact of buildings is startling. Sustainable design seeks to mitigate this negative impact through the use of environmentally sensitive design and construction practices. The goal of sustainable design is to produce green buildings that are "environmentally responsible, profitable and healthy places to live and work.

With BIM, much of the data needed to support performance analysis is captured naturally as design proceeds. With BIM, designers can analyze how a building will perform, even in the early stages of design. Armed with this information, they can evaluate design alternatives quickly and make better decisions for greener designs. By streamlining design and analysis, BIM facilitates the calculations needed to optimize building performance.

A BIM-based design model carries a wealth of information necessary for many other aspects of sustainable design. For example, the ability to create drawings and details directly from a model (and have the software automatically coordinate these drawings and details with the model) improves the efficiency and accuracy of green certification. Schedules of building-material quantities can be obtained directly from a model to determine percentages of material reuse, recycling, and salvage. Various design options for sustainability can be pursued in parallel and automatically tracked in a model. Advanced visualization techniques can be used for solar studies and to produce 3-D renderings and construction animations of a green project. A digital 3-D model supports better understanding and collaborative communication among the various stakeholders in a green partnership (the architect, owner, consultants, review bodies), [See figure 4].

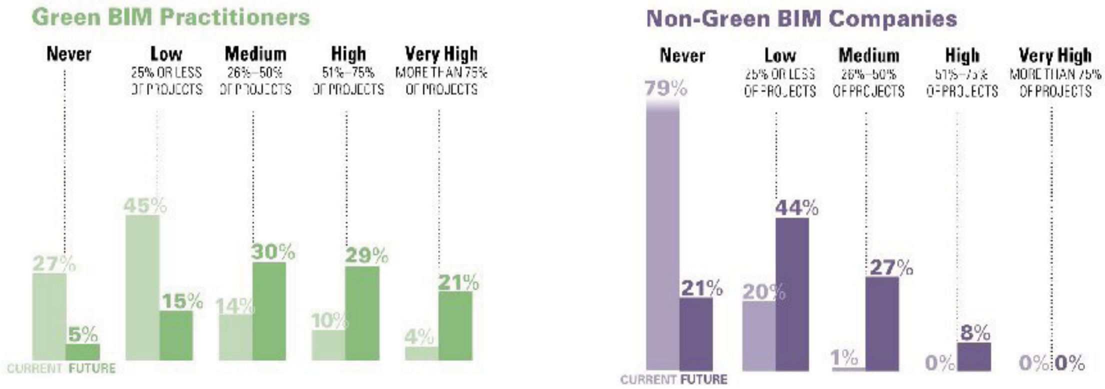
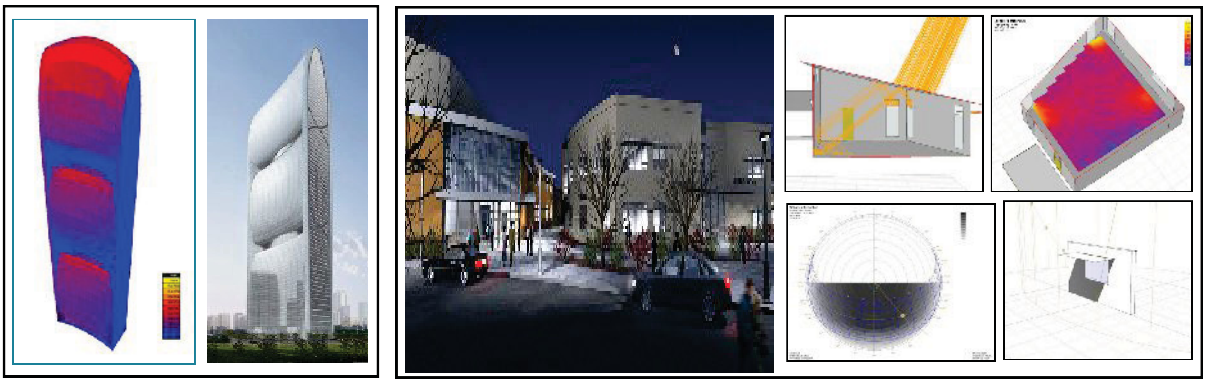


Fig. 4: Current/Future Use of BIM Model – Driven Prefabrication, (SmartMark Report , 2010).

4.1 Green Building Studio

Green Building Studio (GBS) is a pioneer in the field of easy, basic energy simulation from design models, [See figure 5(a,b)]. As both a company and a Web-based service of the same name, GBS includes a protocol for translating information from CAD software into the industry-standard DOE-2 energy simulation engine. Because an energy model requires data that isn't typically defined even in BIM files, much less conventional 3D CAD, GBS fills in the gaps with many default assumptions. "Most of the tools that are moving forward are still engineering tools," said John Kennedy, president of the company, referring to their intended use for analyses of fully developed designs by trained engineers. He added, "The whole point of this tool is early-stage modeling", (Nadav M., 2007).

Kennedy has created plug-ins for Autodesk's Architectural Desktop and ArchiCAD that assist users in defining HVAC zones and validating the BIM model to increase the chances that the energy simulation will provide useful results. This capability is integrated into Revit, so no plug-in is required. The software generates a file in gbXML format (an information exchange protocol developed by GBS) that the software uploads to GBS's server for analysis. Minutes later, the designer can download the results of the model. GBS allows users five free runs; more runs are available for a nominal fee. GBS recently introduced a "design advisor" service that automatically generates proposed modifications to the design and allows users to experiment with a small number of alternatives. GBS also makes its DOE-2 input file available for download, offering engineers a shortcut for running their own early-stage energy models, (Nadav M., 2007).



(a) (b)

Fig. 5:

(a)The Pearl River Tower designed by SOM for construction in Guangzhou, China, includes integrated wind turbines and photovoltaic panels to offset its energy use. Inset is an Ecotect model showing the amount of solar radiation on the tower's various surfaces, (Nadav M., 2007).

(b) BIM tools provide thorough information to guide and improve design solutions. In the design of American Canyon High School, BIM facilitated our design decisions and helped achieve our sustainable goals, (Aaron J. AIA. LEED A., 2008).

4.2 Benefits of Green Design with BIM

The thoughtful designer can use BIM models to save resources AND money for project owners by incorporating analytical studies into the early design phase.

Informing Construction and Operations: Construction to Operations Building Information Exchange (COBIE). COBIE will provide the data exchange standards which can be imposed on the manufacturing industry, allowing increased and functional exchange.

Walking the Walk: Within that model, users can "walk through" the spaces in real time and identify potential conflicts between building systems. Importantly, even without access to the more complex design software that creates the model data, subcontractors can visualize how the building systems will go together, (Novitski B.J., May 2009).

Automated Documentation: The use of BIM raises a host of issues around liability and intellectual property and is forcing the industry to rethink the concept of contract documents, (Matthew B., 2009).

Analytical sun studies: Conducting a sun study helps the designer to evaluate and refine his project to effectively use daylight sources, (Matthew B., 2009).

Continuous control of usage of resources: Quantities and detailed data about building components can be generated, providing the architect and the owner with valuable information about the materials used, (Matthew B., 2009).

What-if scenarios for design optimization: The ability to run different scenarios supports the green design process, (Matthew B., 2009).

Computer energy simulations: , (Matthew B., 2009).

- Computer energy simulation is used throughout the design process to assess the building's energy conservation value and construction costs.

- Architects and engineers can collaborate to generate many alternative concepts for building form, envelope, and landscaping. This allows focus on minimizing peak energy loads, demand, and consumption.
- Typically, heating and cooling load reductions from shading devices, better glazing, insulation, efficient lighting, day lighting, and active and passive solar systems allow for smaller and less expensive HVAC equipment which, when well designed, can result in little or no increase in construction cost compared to conventional designs. Simulations are used to refine designs and ensure that energy-conservation and capital cost goals are met and to demonstrate compliance with regulatory requirements

5. Final Thoughts

Growing awareness of the impact of buildings and infrastructure on the environment has increased the need for building-industry professionals to embrace sustainable practices. Sustainable design is a major trend driving process change within our industry, requiring a workflow that provides more information earlier in the design process. BIM is poised to facilitate this change because it enables an integrated design workflow, linking design and analysis. As the use of BIM in the building industry grows, building designs and outcomes will become more accurate, buildable, predictable, and sustainable, enabling the cost-effective design and delivery of healthy, resource-efficient buildings and mitigating the carbon footprint of our built environment.

The perfect ideal of BIM may not be attainable, but pieces of it are definitely coming together. Projects-and the environment-are benefiting from more cohesive teamwork and a greater degree of interoperability among software systems. Architects are receiving better, earlier energy-related analysis; engineers are providing more focused expertise during design; builders are reducing waste in construction; and facility managers are increasing the efficiency of their operations. And many of those experiencing the benefits of technology and teamwork have visions of still more capabilities and benefits in the future. At a time when economical use of resources is critical, to the survival of the building trades and, potentially, to the survival of human and biotic communities, it makes sense to take a new look at how we create efficient buildings. The technology is available today to help architects find the best solution. And as the demand for "more green" increases, developers will expand these analytical tools to take advantage of the power of BIM. One more thing, while you are designing the greenest buildings, why not do it on one of the world's greenest computers? In addition to their power and ease of use, Apple's lineups of notebooks are energy efficient and built with the environment in mind.

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A WALKTHROUGH OF LARGE SCALE AND COMPOSITE HAZARD

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ABSTRACT: *The composite hazard consisting of flood, debris flow, deep collapse, shallow collapse, and landslide dams was responsible for the massive scale of the disaster in Siaolin village from the typhoon Marakot in Taiwan. This kind of disasters are usually not well understood by the general public; however they often cause huge damage due to the lack of vigilance regarding such disasters. In this research, we proposed a game-based walkthrough approach to simulate a large scale and composite hazard to promote of disaster prevention. The system uses a storytelling style combined with a walkthrough of the disaster in a virtual environment. The disaster introduction method consists of two steps: the introduction step and the simulation step. The introduction step introduces the process and details of the disaster through voice narration and reading material. Then the simulation step provides the walkthrough and visualization of the disaster. The proposed method provides a storytelling based, interactive environment, which can motivate people to understand the disaster and help them realize the importance of disaster preparedness. Through this system, we are able to understand the whole course of the hazards, raise people's awareness of the disaster and thereby reduce the damage caused.*

KEYWORDS: *first person, interactive, experience, digital storytelling, scenario, disaster preparedness*

1. Introduction

The typhoon Morakot caused severe damage to Taiwan between August 6, and August 10, 2009. Siaolin village, located in Kaohsiung County, bore the brunt of Morakot. Nearly 400 people were killed. When the typhoon hit Siaolin village, many different kinds of disasters occurred sequentially, including flood, debris flow, deep collapse, shallow collapse, and landslide dams. This kind of disasters is defined as composite hazard. A composite hazard is a large scale and complicated event; people who have no experience of dealing with such a hazard cannot comprehend what really happened. Even the people who survived the disaster found it difficult to understand. Therefore, understanding the whole course of the composite hazard can effectively help raise awareness about such disasters and improve disaster preparedness; this can significantly reduce the injuries and deaths caused by such a disaster.

The methods for disaster education and disaster information propagation can be divided into three categories: text based, video-based and in class methods. Text based education is through the publication of brochures. However, people can easily forget the contents and such brochures cannot accurately present real hazard circumstances. The research of Zhang et al. (2004) indicated that students often feel bored of text-based learning and this could prevent them from clearly understanding the subject . Monahan et al.

(2008) mentioned that traditional text-based learning shows a poverty of the most important elements involved in learning: the social interaction with other students. Video based education involves visuals of scenes of the disaster and the presentation of course content through multimedia techniques, which can engage students more in their learning activities . However, the audience is unable to become personally involved due to lack of interaction. Taking disaster preparedness classes could guarantee some degrees of interaction but the class takers may not understand how the disaster really happens. Recent research suggests that training classes is costly in terms of time and money, and even in the classroom students only learned from printed documents, still far from the real crisis situation .

Though these three types of disaster education can equip people with some disaster related knowledge, there is no comprehensive way to enable people to really understand the disaster and become aware of some critical signs before the disaster. Nowadays, with the help of new computer technologies, disaster education has become more flexible with the use of game and virtual environments (Sanders and Rhodes, 2007). Computer games have always been successful at getting peoples' attention (Monahan et al., 2008); therefore a game-based walkthrough of the disaster could be the right solution for increasing disaster preparedness among people.

Therefore, a walkthrough of a complete composite hazard through interactive digital storytelling proposed in this research. The whole course of the composite hazard is divided into six sequential scenes to explain the cause and effect of the disaster. Each scene is presented in two steps: The system first introduces the details and background of the on-coming disaster through text, voice, and images. Next, the user can experience the disaster in an interactive virtual environment. In the virtual environment, users can view the process of disaster through different camera views. The proposed method can impress people, focus their attention on the hazard and also provides accurate information to help them understand complex and large scale composite hazards.

2. Related Works

Many research studies have indicated that games can increase the interest of audience. Game-oriented education is helpful in raising users' awareness about disasters. Clerveaux et al., (2010) have designed a board game called the Disaster Awareness Game (DAG) to promote disaster awareness in multicultural societies. Preliminary research results indicate that DAG is an effective tool in educating children about hazards, and measuring levels of disaster awareness . The game is also interesting enough to hold children's attention. Haferkamp and Krämer (2010) utilized a serious game to simulate the training scenario of specific knowledge and social skills, such as communication and decision-making, which should be taught to reduce damage from catastrophes. Zhang and Gu (2009) tried to develop a computer game for disaster education and were successful in constructing a virtual context and exerting a subtle influence on players. However, this game has also encounter problems in engaging players in the game . Virvou and Katsionis (2008) have also pointed out that educational software games have to be usable and be liked by all students, and that a virtual reality game is definitely usable and likeable with more scope for improvements in usability and likeability .

Computing and communication technology has made a revolutionary change in engineering education systems, and has improved the student learning experience . Many researchers have tried to figure out the feasibility of virtual environments (VEs) in learning applications . Bailenson et al., (2008) presented some evidence to show how VEs enable transformed social interaction (TSI), the ability to improve learning by changing online representations and contexts. Balamuralithara and Woods (2009) illustrated that a virtual laboratory for engineering student's practical learning has advantages including flexibility, the explanation of theoretical concepts, and repetition. Monahan et al., (2008) developed a virtual reality e-learning system called CLEV-R, a Collaborative Learning Environment. This system provided communication tools to support collaboration among students in order to keep them engaged in their learning and maintained their interest by making up for the lack of interaction in traditional e - learning.

In other fields such as medicine, virtual reality simulator training on laparoscopic surgery helps novices and less experienced laparoscopists improve their skills and reduces the operation time . This research further suggested that simulator training should be considered before trainees carry out laparoscopic procedures. Another study in medicine illustrated that the clinical setting performance of residents trained on a colonoscopy simulator prior to their first patient-based colonoscopy is notably better than controls, demonstrating skill transfer when they start dealing with live patients .

Augmented reality (AR) is a technology that allows the virtual objects such as 2D scenes or 3D models to enhance and augment visuals of the real world by technology. Through AR technology, the mixing of the virtual and reality can allow users interact with the environment through devices . Arvanitis et al., (2009) started the CONNECT project which constructs an interactive learning environment that aims to integrate the use of physical objects that are computationally-augmented and to support and encourage face-to-face interaction between students and virtual objects. Billinghurst et al., (2001) provide the MagicBook which could tell a story to children using physical object and easily transport users between reality and the virtual scene in the story. Kaufmann and Schmalstieg (2003) developed a 3D geometric construction tool for mathematics and geometry education based on an augmented reality system called Construct3D, and found evidence that the system is easy to learn, encourages experimentation with geometric construction and improves spatial skills . They further indicate that the biggest advantage of the system is students could see real 3D objects usually shown on paper.

Existing research shows that interaction is the most important part of education to attract the users. Game-oriented simulation helps improve user experience, this has potential for improving disaster preparedness. Therefore, this research proposes a system developed using a game engine to walk through the complex composite hazard

3. Game Engine

In this research, we used a game engine to simulate the composite hazard process. The game engine is the heart of a game and consists of several components . The common architecture of a game engine consists of five major components: the authoring tool, the physics engine, the rendering engine, the user interface (UI) and the audio engine .

The physics engine handles physics calculations, its major function is to deal with low-level details of physics simulation and act like a big calculator. For simulating physics the engine computes the mathematical functions, however, the engine does not knows what needs to be simulated. The typical physics engine has two important functions: collision detection and multibody dynamics. Collision detection is the process that determines contact between objects, while multibody dynamics computes the dynamic motion of objects which are connected to each other by joints or exist independently . Both functions use mathematical methods that are derived from physical laws. However, the processes inside the implementation of a physics engine are encapsulated and invisible to the designers; the designers only needs to ensure that the simulation effects act as per his requirements, and then control specific parameters and data to the physics engine to generate the required effect .

The rendering engine is responsible for drawing the 3D world and displaying it on the screen. The work of the rendering engine can be described in three main steps . The first step is to transform 3D data of game objects into 2D data in screen space, which requires two transformations. In the first transformation, the engine converts 3D data in the game world into 3D data in the coordinates of the view world, which is associated with the camera in the game world. It decides which view will be seen by the player on the screen. The second transformation converts 3D data of the view world into 2D data in the screen world. This process is called *projection*. In the projection, the 2D data is made available to be drawn as pixels on the computer screen. The second part of the rendering work is to exclude portions of the data that are invisible to the player. This process includes *culling* and *clipping*, which can decrease the computational costs of a rendering engine. The third step is to draw the 2D data in the screen space onto the computer screen. This process is called *rasterization*, it takes up the most time of the total time spent in rendering. The *rasterization* process computes the displayed colors of the pixels through the calculation of several shading effects, including materials, textures, lighting, specular effects, transparency, ray mirror, and other special functional effects.

The function of the audio engine component is to generate sounds while the game is running. Audio can be extremely important for a game's atmosphere, and can heighten player satisfaction and enhance the quality of a game. This audio can include recorded sounds, interface sounds, and sound effects . For example, voices and background music are recorded sounds, while button clicks are a kind of interface sound, and explosions and the sound of brakes are sound effects (FXs). To generate these sounds, an audio engine has to load, edit, and mix the sound data. An audio engine is usually provided with several functions to generate game audio, such as playing, mixing, 3D sound (stereo effects), the Doppler effect and the fading-out effect.

The component that represents interaction between game objects and a player is called the user interface (UI) which can be divided into invisible interfaces and visible interfaces . The invisible interfaces are the UIs which have no on-screen features; for instance, control triggers using a mouse or keyboard, which can be used to select, move items, navigate in a virtual environment, operate character movements, communicate with NPCs (non-player characters), etc. The visible interfaces are the UIs that have on-screen features, such as selectable menus, the health meter of a character, and any other on-screen information that is provided to the player.

The physics engine, the rendering engine, the audio engine, and the UI are the basic components required to develop a realistic physics-based simulation or virtual environment. Some frameworks of integrated development environments (IDE), such as Microsoft XNA, provide an integrated library for utilizing these four components to develop simulations or games. However, programmers still need good programming skills and effort to build a robust and stable simulation system. Therefore, in order to help game designers avoid much effort and time in developing the complex foundation and structure of a game program, advanced game engines provide authoring tools. The game designers just need to load the game content (3D models, textures, or sounds), specify parameters, and design the game logic via this authoring tool. This allows game designers to use straightforward commands or actions to order the game engine to execute detailed programming jobs. Thus, the game designers can spend their time on more relevant parts.

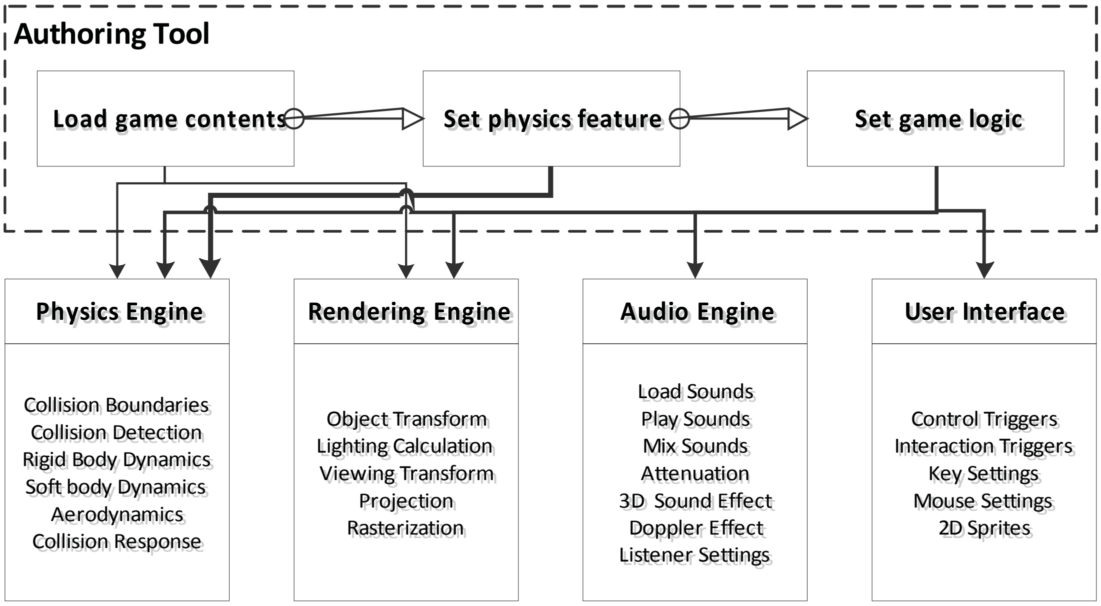

Fig.1: Game engine architecture.

4. Methodology

4.1 Navigation Process of the Composite Hazard

The composite hazard is a large scale and complex event. In order to present the whole course of the event clearly, the entire process of the hazard is divided into six sequential scenes. Each scene is presented in two parts i.e. the introduction and simulation of the hazard. In the introduction, we describe the partial course of the hazard through text and narration. In the simulation, we construct a virtual environment showing the hazard occurring to allow the user to walk into the partial course of the hazard and see what is happening.

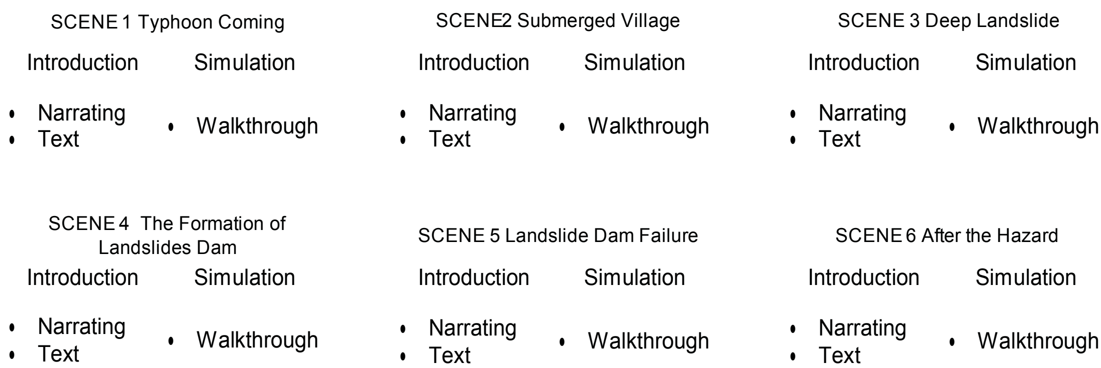

Fig. 2: The navigation process of the composite hazard.

The course of the composite hazard that happened in Siaolin village is divided into six parts: the typhoon's arrival, submersion of the village, deep landslides, the formation of landslide dams, landslide dam failure and the aftermath of the hazard. The first part of the hazard course is the typhoon's arrival. This part demonstrates the beginning of the hazard. At the beginning, the typhoon brought continuous rain and the flooding submerged a road near the village. The second part shows the village submersion and the people of the village escaping to a safer, higher place. The user can easily understand the process through different views of the virtual environment. The third part occurring just after the second part, was a deep collapse of the mountain near the village. The landslide destroyed a bridge and barrier and a stream then a landslide dam appears. The fourth part is a depiction of the emerging landslide dam. The fifth part shows landslide dam failure, and from the failure, the village is totally obliterated, nothing remains except some gravel. The last part allows the user to walk through badly damaged village.

4.2 Visualization of the Composite Hazard

For realistic visualization of the disaster, three major techniques are used in this system:

Particle System: it is a term in computer graphics and describes techniques to model a class of fuzzy phenomena that are difficult to present by traditional rendering methods . Particle system techniques are widely used in three-dimensional graphic systems for simulating fire, smoke, moving water, explosions, snow, rain, dust, grass, etc. An emitter which might be a cube or a plan is the source of the particles and controls the particle system's position and motion. Particle behavior can include the spawning rate, the velocity of the particle, the lifetime of the particle, etc. To simulating the required effect, the particles would update in several steps and then be rendered out. The particle will first be created from the emitter position and initialized to the value set for their behavior. During the particle's lifetime, particle behaviors such as trajectory, velocity, position and motion are controlled by physics such as gravity, external forces and collision between particles. The collision detection could also apply to the particles and environment or 3D objects. At the end the particles will be rendered.

In our walkthrough system, we used the particle system for simulating the rain, dust, fog, smoke and some landslides effect. The particle system is a good technique for making the virtual environment more realistic and conveying the impact of the disaster.

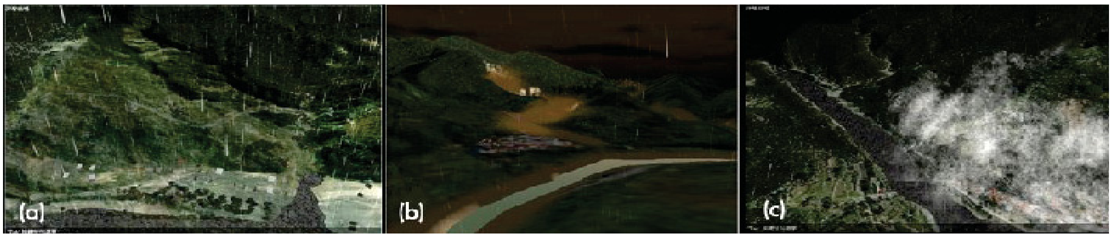

Fig. 3: Visualization result of the disaster using particle system

Multibody Dynamics: it is mainly used for computing physical feedback between multiple bodies in mutual contact with each other or connected to each other by joints . The simulation of multibody dynamics is generally composed of rigid body dynamics and constraints. By solving the equations of motion (which are used to describe the dynamical behavior of multibody dynamics), the simulation can calculate the behaviors of a multi-body during each time integration .

We used multibody dynamics to simulate the flood collapsing the houses of the village. Houses are broken into different parts, connected by joints. When the flood approaches the house, an external force would hit the house, and then the house will collapse as we want according to the restrictions of the joints.

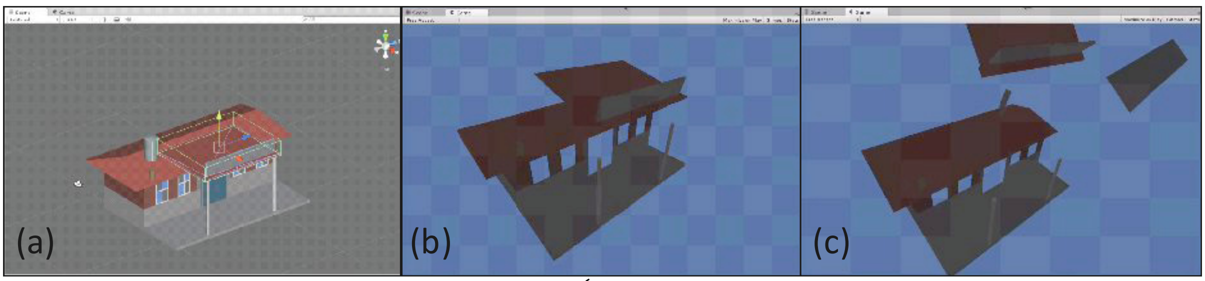

Fig. 4: Using multibody dynamics to simulate the collapses of buildings and houses in the village: (a) setting up the multibody; (b) and (c) screenshots of collapse simulation.

Shaders: Computation of the rendering effects by following a set of software instructions is called the shader. A shader is flexible. It drives and programs the graphics pipeline of the graphics processing unit . With the shader the user can program any effect they want, and this feature could replace the traditional fixed-function pipeline which only allows common transformation and pixel-shading functions.

We used shaders to simulate the deep landsliding process. The surface of the earth is totally different after the disaster, so after the disaster we change the surface of the earth. And the process of the deep collapse is simulated by shader. We demonstrate it through the effect of the surface sliding along the mountain's tilt angle.

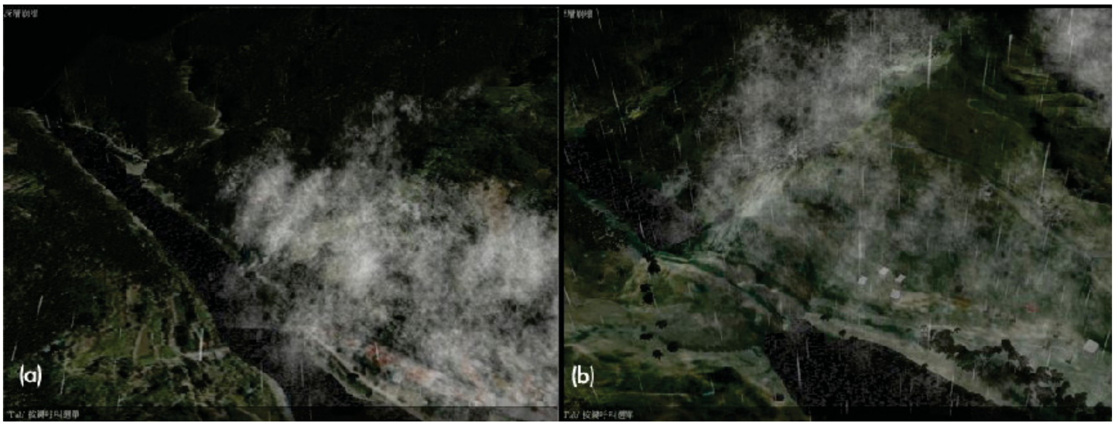

Fig. 5: Using vertex and geometry shaders to visualize the deep landsliding effect.

5. Implementation

5.1 Unity3D

In this research, we use Unity 3D as the game engine for simulating the composite hazard. Unity is an authoring tool for creating games or other interaction content, such as architectural visualizations or real-time 3D animations. This tool can run on Windows and Mac OS X, and Unity 3D games can run on multiple platforms. The most important part we used in our system is the web-based player. Unity 3D can produce browser games that use the Unity web player plugin. This kind of browser games can be publicized widely because the user only has to connect to the internet and open the browser to play. Thus our system could be used broadly.

5.2 Developing the Virtual Environment

The 3D virtual environment was constructed based on the scene of Siaolin village before the hazard. The scene consists of terrain, skybox, lights, and 3D assets such as buildings, avatars (to represent the characters), textures that have to be applied on the 3D models, terrain, and audio effects.

We have constructed six different environments to present the six parts of the hazard. Each part has different settings depending on the distinct hazard type. The first part illustrates the hazard's beginning, continuous rain is shown through the particle system, and the rain will react when the particle touches the ground because of boundaries collision. The rain has been set to occur from the first part to the fifth part. In the second part and the fifth part, we have modified the water level of the stream by modifying the surface of the water. The landslide of the third part is demonstrated using the shader.

To accurately present the environment of Siaolin village before and after the hazard, we have used Google earth information to construct the virtual environment.

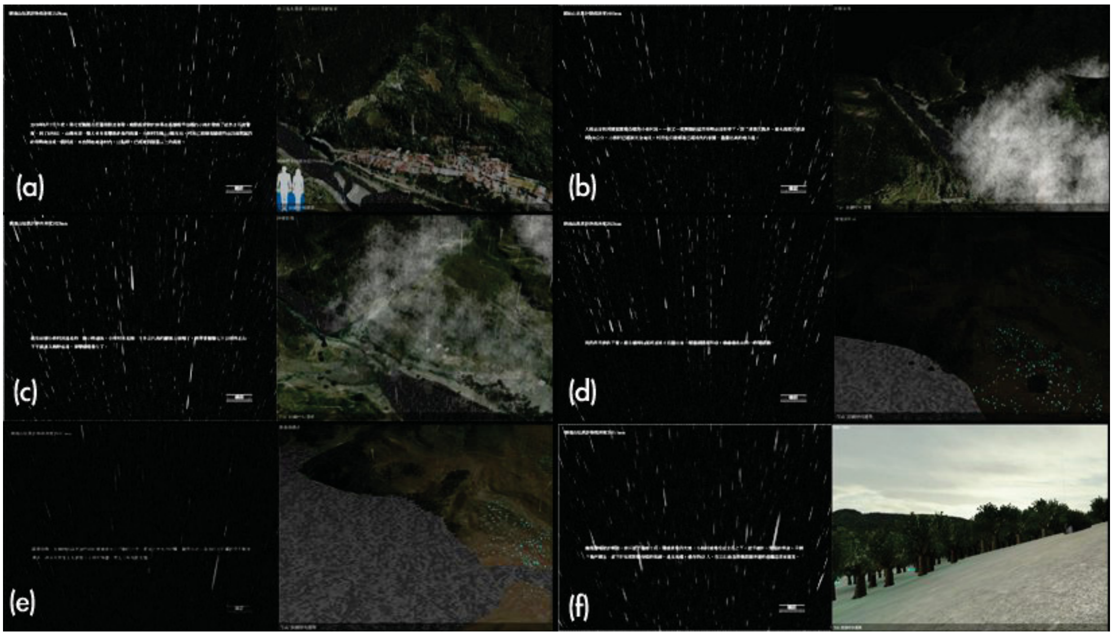

Fig. 6: Screenshot of each scene in the composite hazard including introduction and simulation parts.

6. Conclusion

In this research, we developed a walkthrough system of the composite hazard that can help people understand the entire process of disaster and increase their awareness and knowledge of the disaster. Developed based on Unity 3D, the system is game-oriented and provides real-time interaction to raise people's interest in understanding such a damaging composite hazard. The developed system can also run online through the internet and executed on browsers. We separated the entire process of the composite hazard into six sequential scenes to let people clearly understand how it happened. A two-step navigation method is provided for each scene. The introduction part uses storytelling to provide the user with basic information about the scene and disaster causes; then the user can experience the disaster themselves from different camera views and by walkthrough navigation. The proposed method can make a deeper impression on the user and therefore effectively raise their consciousness about this kind of hazard. Future work will focus on improving the realism of the disaster simulation, which can improve the user experience and impact on people regarding this kind of composite hazard.

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MODEL BASED CONSTRUCTION SITE MANAGEMENT

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ABSTRACT: *A joint research project of RIB Deutschland GmbH and BAUER Spezialtiefbau GmbH investigates the functionality and benefit of digital tools in the field of Geotechnical Works. A model based construction management system has been applied to a excavation pit construction site. The "BAUER 5D"research project shall clarify whether and how intelligent digital tools like the RIB software "iTWO" (5D estimating software) can systematically assist the management on construction sites in the field of Geotechnical Works. The approach is to create a 3D model of the whole building structure first, then, schedule working steps, assign costs and systematically link components to the bill of quantity (BoQ). It enables further estimation, control and billing proceedings to ease and automate managing on site. Consequently, certain but inevitable extra effort has to be considered to virtually model the building structure. Once the above mentioned integrative 5D management procedure will be implemented on site, a direct benefit might be to assist the site manager by simpler and faster control and billing procedures. Apart from that, it will have to be approved that saving of time and costs during the construction phase will amortize or even exceed those additional costs for extra effort in the planning phase. However, since exact quantities stand for exact costs, from a rather strategic perspective a lower quantity risk will be a valuable benefit. Another advantage might be enhanced quality in complex working procedures as these have been planned beforehand and realistically in 3D.*

KEYWORDS: *CONSTRUCTION SITE MANAGEMENT, GEOTECHNICAL WORKS, PORCESS INTEGRATION, CONTROLLING, 5D*

1. Introduction

Most of the building project contracts in Germany are based on bills of quantity (BoQ). In principle BoQ have been prepared by the client respectively from its assigned consultant within the tender phase. The later contract will then be based on this BoQ which also will be the binding for the billing. For this reason BoQ are often made with the focus on billing units than on building process-based items. Consequently it will take time and persuasion work to get to a "100%" model based integrated method for construction sites, which is more efficient in combination with an adequate model-based BoQ which would require first a parameterized model. For the time being the client does not necessarily consider such a "parameterized model", not even a 3D model since anyhow such extra effort isn't demanded by the procurement law in Germany or proven to become amortized within the same project. Furthermore, having already a parameterized model it would inevitably mean that all management processes in conjunction with the BoQ will be handled electronically only. But this advised solution could only be a co-solution in line with a classical paper BoQ not to exclude any contractor from offering a quotation. These circumstances don't promote the 5D process, understandably. But a recently finished research project in Germany called "ForBau", financed by the Bayerische Forschungsstiftung, could proof that required digital tools and methods are available and how they can be used jointed effectively. And as technical development and education is under dynamic progress tools and methods will become more economical, and in addition personnel will be easier with electronics with time. Thus, the 5D model based construction site management is being assessed as realistically applicable yet and as economic method to gain great benefit, e.g. because exact quantities stand for exact costs.

The focus of the hereunder described investigation was how to implement a "classic" BoQ contract into the RIB iTWO software, consequently based on a fully parameterized and process-oriented 3D model. Another main purpose to examine was how to partly automate the billing process complying with the default hence fixed BoQ. Eventually, experiences shall be gathered and evaluated to quantify benefits respectively time saving created, especially for the site manager, who must be supported to manage his job site in accordance with both the logical and intuitive view of processing the construction step by step, independent of any BoQ, and of measuring and charging built elements accordingly. Thus, even if the project would be functionally tendered a complete geometrical and process control would assist to evaluate the efficiency rather automatically and more exact than without a parameterized model. Additionally the cost and performance report, usually required weekly, could be generated automatically on condition that data monitored at site will be put into this new 5D management tool.

2. 5D-Process

2.1 3D Model - CAD

Already when setting up the 3D model in CAD, the consecutive activities from the realistically planned construction process have to be considered in advance. That means that the arrangement of construction elements has to reflect the whole building process in its discrete sequences and has to match with billable units. That does not necessarily mean that each billing unit has to be modeled, e.g. reinforcement can be an attribute to an element even if it is a billing unit on its own. But, due to the stated "classic" BoQ which is non-conformant with the step-by-step process, single building elements may consist of two different billing units and thus have to be designed as two separate BoQ components.

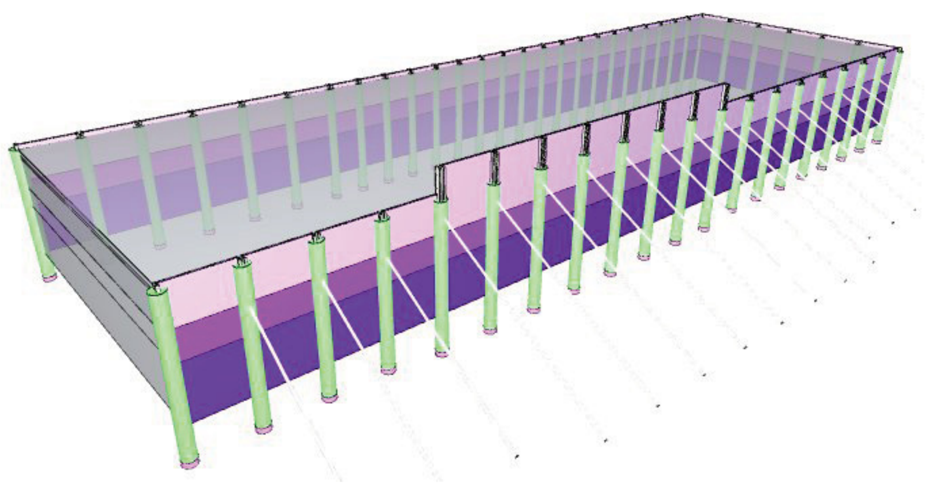

Fig. 1: 3D Model (source: RIB Deutschland GmbH)

All those building components have to be fully parameterized in CAD to allow an automatic assignment to the alphanumeric system of RIB iTWO. Any component comprises a clear identity. That is important for later amendments and also for determining exact quantities hence correct costs in the alphanumerical system.

Besides, any parameter based analysis can be made either directly in the CAD software or in RIB iTWO.

As contractually specified Bauer Spezialtiefbau was in charge of the detail planning for execution of the pilot excavation pit project. For approval process at client side 2D plans and drawings had been demanded. Therefore 2D drawings were handed over, which had been derived from the 3D model as free sectional elevations. If the geometries have changed for some reason, also the 2D planning would have been updated by changing the geometries in the 3D model.

From the CAD system the 3D model has been exported as cpiml (construction process integration) with all the geometrical information and all the parameters of single components.

As a by-product of this pilot work the herewith implemented parameterized construction elements, by putting into a library, are already integral constituent of a template which can serve for future projects.

2.2 5D Model: 3D Model + costs + time

2.2.1 Real quantities – cost reliability

In RIB iTWO all the BoQ components have so called intelligent quantity queries. As the BoQ components are still fully parameterized when imported into the 3D viewer of RIB iTWO the construction components will be automatically assigned to the items of the BoQ. That means that at this point we produce "real quantities" in the alphanumerical system.

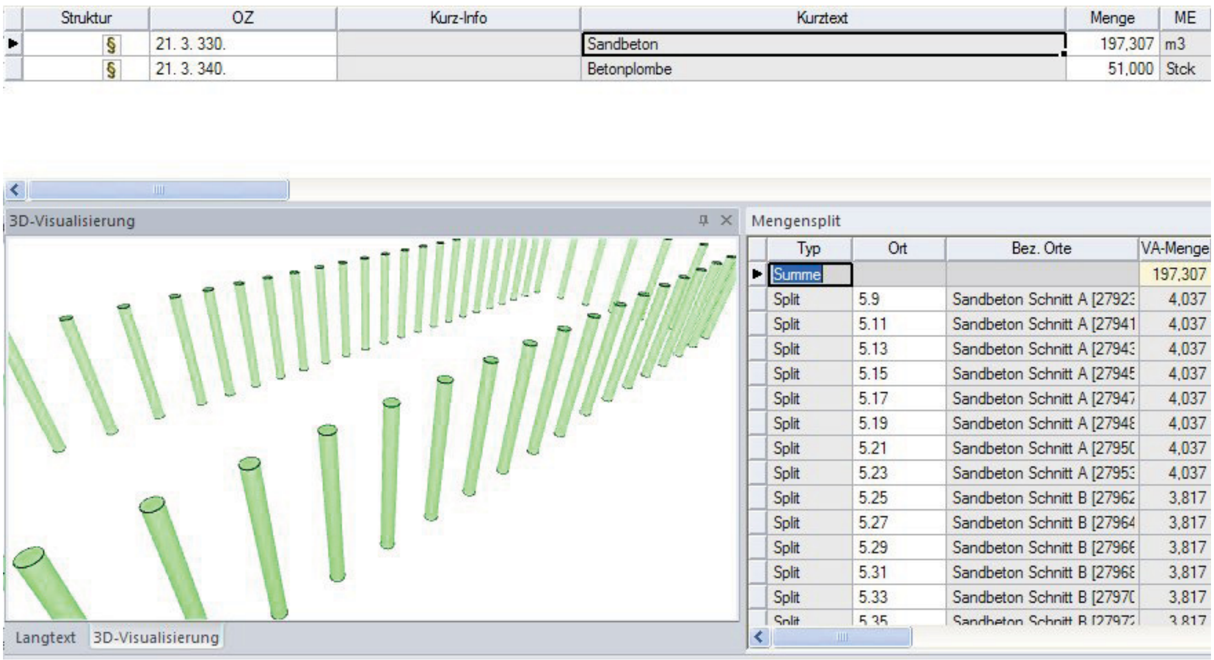

Fig. 2: Bill of Quantities with construction components (source: RIB Deutschland GmbH)

Because the cost estimation had been already linked to the single BoQ items beforehand, subsequently the implemented real quantities automatically create exact estimated costs. Cost estimation is therefore inseparable connected with modeled quantities what gives high reliability even for control during the execution of works.

Quick evaluations and objective data are the basis to assist the site manager. Production data obtained and changes in the building process or structure have to be reported respectively documented anyway. To avoid extra effort – the site management should be relieved – in future such data have to be entered into the management software directly and only there. At the same time data are input the site manager can get exact information about hours, plant utilization, material quantities, all for the complete site.

In case any changes have been applied to the 3D model (in CAD), a new cpixml file will be imported into RIB iTWO and the quantities will be actualized automatically by the clear identification of the components and their parameters. Changed quantities then will also change estimated costs.

2.2.2 Model based scheduling, simulation and controlling

The scheduling for the pilot construction site was created in ASTA Power Project and then imported to the activity model of RIB iTWO. This is not only a simple "transfer of data" but a dynamic connection between both systems.

Linking BoQ components to the scheduling of execution, and having linked those already with the construction elements the result is a full 5D model.

One of the soft benefits for the site manager is to "see what you build" (and what you have built), detailed in 3D plus timing plus costing and evaluable for several activities. At each point it's possible to request a new target planning of resources like hours, plants, material etc. in the single activities.

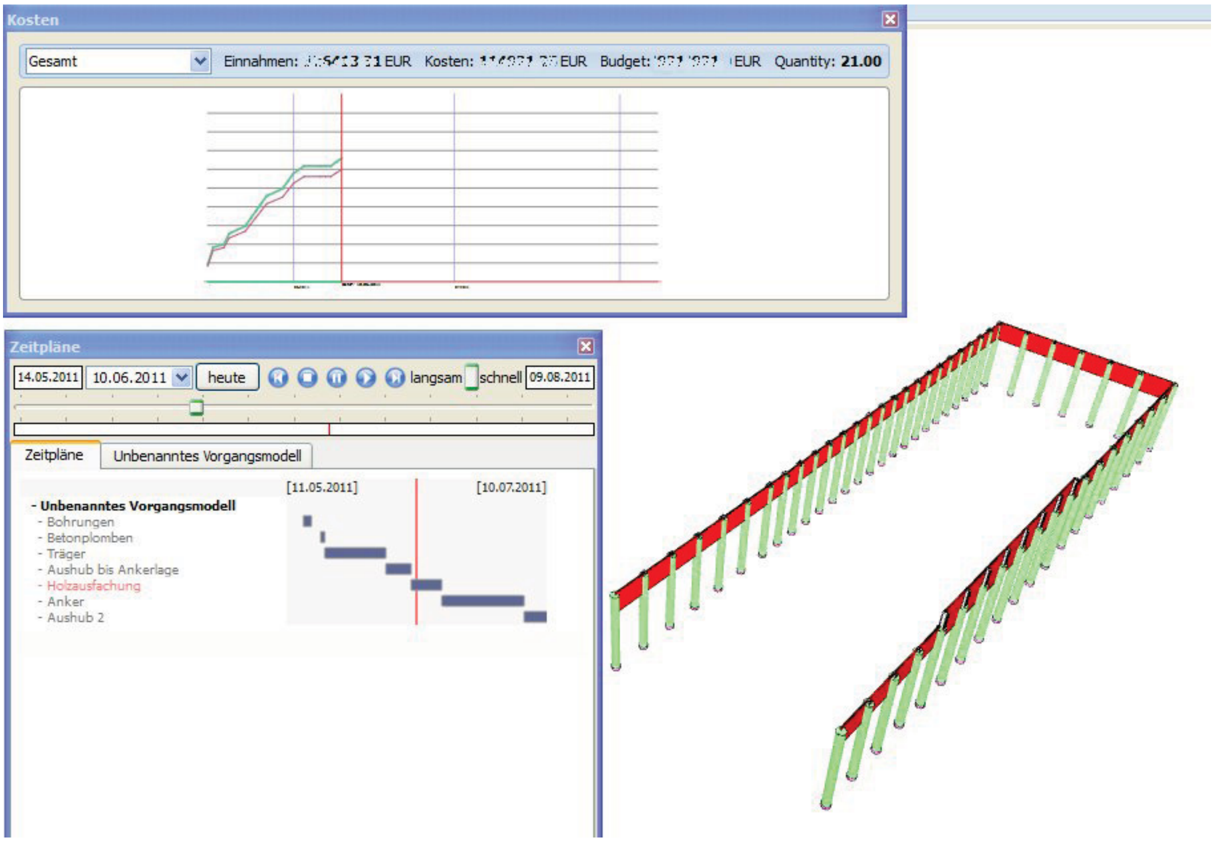

Fig. 3: 5D Simulation (source: RIB Deutschland GmbH)

Comparing "virtual reality" and "reality" hence planned and actual execution allows the project manager to control not only the schedule, but also the use of budget.

Entering the progress of the site in the form of executed quantities directly into the model based activities, executed quantities can be billed directly out of the software complying to the BoQ.

Finally the estimated costs on a certain due date can be compared to the real costs derived from the financial System (SAP).

3. Conclusion

Relevant planning, control and billing processes have been shifted from "classic" tools to a model based construction site management tool. Therefore a 3D model had to be designed, from which any 2D execution drawings can be produced by pressing a button.

The benefits for the site manager to control the works model based are more comfortable than to handle only on BoQ elements, which cannot reflect the scheduling of the site. The integration of all information, in the classic models distributed in various programs and tools, in only one program offers several advantages, above all a more precise and in time control.

Extra effort for using the 5D management tool has still to be evaluated and compared with the profit on sitewithin the pilot project but possibly do not allow a reliably based decision. Thus, an economic compensation of higher process costs inevitably will have to be proven in further projects.

4. References

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FREE-FORM DESING BY DATA-DRIVEN COMPONENTS

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ABSTRACT: *On the example of the remodelling of a house in Lower Austria, the authors show, how free-from design can be used to solve restrictions of local zoning law, how parametric design can be used to structurally optimize a shell construction by local differentiation of each shell component.*

KEYWORDS: *parametric design, file-to-factory, rapid manufacturing, free-form design*

1. Introduction

Architectural free-form design, though omni-present in the conceptual work of universities and architectural practices, still is a rare feature in the built environment. If such formal concepts materialize, it is usually either a very prominent building brought to life by a huge team of highly educated experts or it is about a small, temporary building, such as a pavilion or booth. The latter usually do not have to meet much of the usual safety and legal standards. Between these cornerstones, there is a surprisingly big gap of *every-day architecture*, which rarely seems to be affected by the idea of free-form design. Also, there might be a lot of reasons for this fact - from design preferences of the involved planners to strict regulations on the appearance of buildings -, this basically has to do with a lack of experience of smaller practices and the reluctance of the building industry and contractors to take on unusual building tasks.

2. Data-Driven Workflow

The authors developed a generic system to design free-form structures. On the basis of a NURBS surface´s UV mesh, a workflow was developed, which allows for evaluating, optimizing and specifying all structural components of such a construction, while designing the form. Non-uniform rational basis spline (NURBS) is a mathematical method, which is widely used in computer aided design (CAD) to model free-form shapes. Two parametric directions, called U and V, are commonly used to describe NURBS surfaces [Rogers 2001]. The structure can be locally optimized, regarding the actual stress analysis and the production process. Each structural component is generated by a script, which is updated by changes of the geometry and, if necessary, by changing load cases. During this process the optimization procedure is performed. Thus an abstract, virtual model of the structural concept is created, which can adapt to nearly any NURBS geometry. The shape of the surface therefore remains under full control of the architect and can be designed by nearly any CAD modeling software (Figure 1).

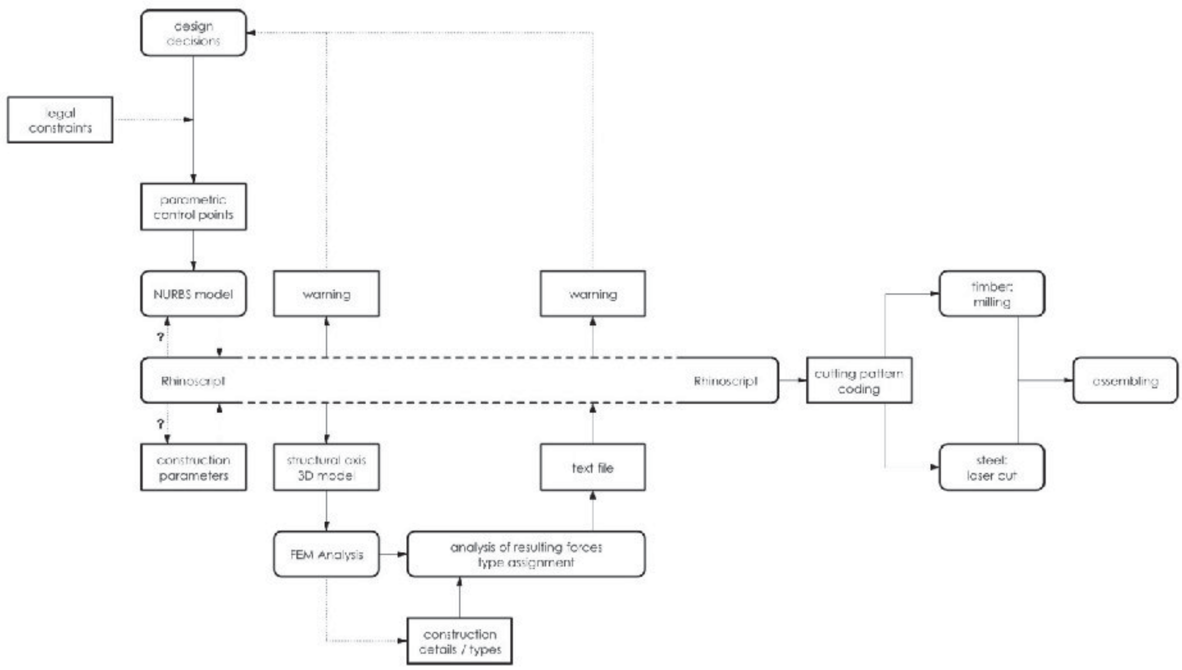

Fig. 1: Workflow diagram, boxes with rounded corners symbolise processes

2.1 Materializing data, zoning law and regulations

The proposed workflow was first applied, when the authors got a commission to build an extension to an existing building in Lower Austria. Beyond the achievement of a formally exciting architectural design idea, the authors found a further design motivation in the simplification of the boundaries given by the zoning regulations of the specific site of their clients. There is a large range of possible free-form shapes, where traditional roof structures would not allow for many alternatives. Further advantages can be found in an increased certainty about the construction, its cost and the simulation of its behavior at an early design stage. Thus the design stays flexible to the very last minute before the actual building process.

2.1.1 Legal constraints

The Lower Austrian zoning law allows deviating from a specified building height, if the surface area of a facade subdivided by its length does not exceed that specified height. Parts of the building skin with an inclination steeper than 45° have to be projected under 45° on the exterior-most layer of the facade and thus contribute to the building height. As Austrian building laws still assume traditional roof shapes, such as pitched roofs, there are exceptions to exceed the building height up to a certain degree for those sides, which are specified as gable. Within these boundaries, there is a large range of possible free-form shapes, where traditional roof structures would not allow for many alternatives. Figure 2 shows a detail from the permission drawing.

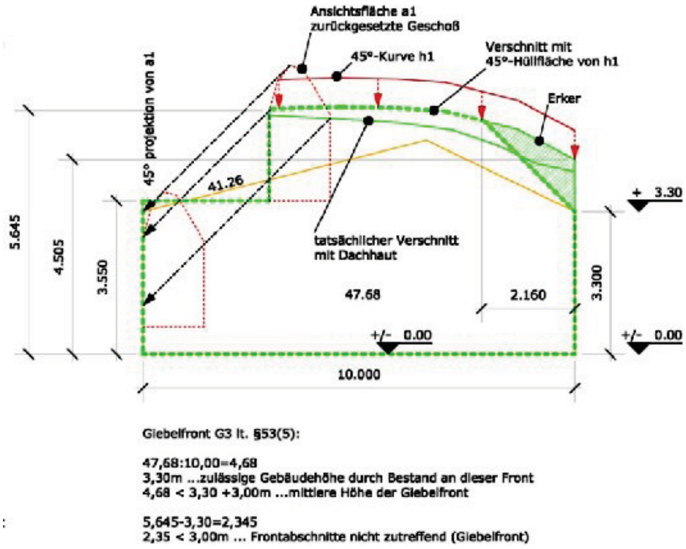

Fig. 2: Detail of the permission documents

The green line shows the projection of the shape on an imaginary façade. The building height is the surface area of this figure subdivided by its length and must not exceed the previously existing building height plus 3,0m. The yellow line shows the previously existing roof.

2.1.2 Design decisions

The final design (Figure 3) of the new skin was found by placing a grid over the L-shaped floor plan, as it was given by the existing building, subsequently "inflating" a NURBS surface to obtain a desired room height at specific areas. Volumes would only be added, where needed. All opaque parts of the new skin would be part of that surface. All transparent parts would be vertical layers, filling gaps between the existing building and the new skin.

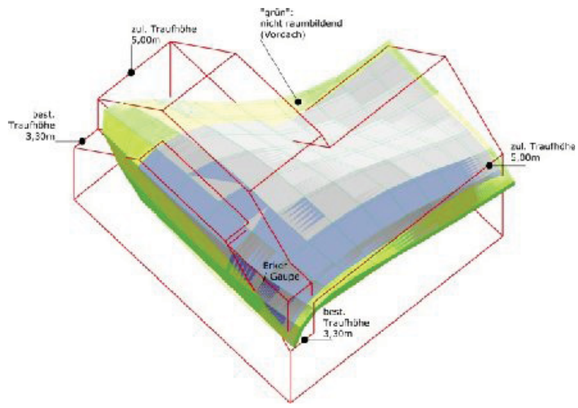

Fig. 3: A possible hull referring to the zoning restrictions

The study shows an imaginary solution with conventional roof geometry vs. the free-form geometry. The green areas are not considered, when determining the building height.

2.2 Structural System Design

When it comes to the construction of free-form design as an opaque building skin, the structural system is often conceived by subdividing the surface into fields of sufficient small and similar curvature, which can be built by parallel ribs. These fields are then assembled. A more generic approach is probably thought of being too much effort and most such examples have been realized as transparent skins. However, parametric design is not only about aesthetics but also about a potential to optimize [Kolarevic, 2003]. The traditional approach misses the opportunity of structural optimization, as it does not easily allow for local differentiation, on the one hand. On the other hand, the primary structure is consequently conceived as a crude approximation to the desired shape and needs multiple layers of primary and secondary construction and a highly customized cladding.[1]

2.2.1 Material options and production technique

Following the idea of reducing effort by planar cutting technology, the authors compared different material options for a similar structure. The cost estimates for a full steel structure were at least twice as high as a similar structure made from wood. To further reduce cost and to get material thicknesses, which can be cut by a CNC-controlled milling machine, glued-laminated timber panels were chosen for further considerations on the structure. The panels should be connected by nodes, made from CNC-cut sheet metal. The timber panels were specified as *K1-Multiplan* from *Kaufmann Holz GmbH* as their structural properties are certified. All metal parts are made from steel grade *S355*. The ribs will be cladded by thin planks, which are then waterproofed by fibre-reinforced polymethylmethacrylate (PMMA).

2.2.2 Construction grid and system

As the planking can be considered as load-bearing, a quadrilateral construction grid can be used, considering the planking as diagonal stiffening of the grid. The structure thus becomes more efficient than the triangulated construction. On the one hand, because it only needs four-armed nodes, where the latter needs five- and six-armed ones, on the other hand, the members of the structure are less likely to bend or buckle as the outer and inner planking stabilizes them. The construction grid could be derived directly from a mesh based on the UV coordinates of the NURBS surface. The ribs of the structure not only serve as primary construction layer, but also as a secondary layer, which describes the curvature of the surface. Thus, the spacing of the grid should be narrow enough not only to meet structural requirements, but also to sufficiently support and form the planking. Using UV coordinates as basis of the construction grid offered a simple and easily accessible way to find a good degree of subdivision for both tasks. This worked at least for this surface, however, the further considerations, followed in this paper, could be applied to other quadrilateral meshes and surfaces. For this project, the surface was subdivided into 13 by 18 fields with 204 four-armed nodes. Each component is labelled by a unique code. Following these codes the wood and steel parts are bolted together by a local carpenter. Three parallel concrete walls on top of the existing structure and a concrete ring take the loads of the shell.

2.2.3 Physical requirements

Another reason to use wood as main structure can be found in the building purpose. As the structure in question is not part of a pavilion or a glazed structure, but the envelope of a residential building, it had to meet a lot of legal requirements, such as thermal insulation, noise reduction and fire protection. Of course it also has to be waterproof. The timber structure allows building the load bearing components into the insulation layer. The form itself was tested for pools, where water would not drain off. The gutters have been integrated into the 3D model of the skin surface and were produced with the timber panels (Figure 4 and 5).

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[1] e.g. the Kunsthaus Graz, Peter Cook and Colin Fournier

Fig. 4: structure with prepared integration of the gutters in the profile of the timber panels

Fig. 5: gutters are completely integrated into the skin

2.3 Local structural optimization

Kas Oosterhuis mentions three possible targets of a local structural optimization for the *Web of North Holland*: point distribution, meaning the spacing of the construction grid, offset, meaning the height of the ribs and the plate thickness. When the *Web of North Holland* was built, only one parameter, the thickness, was taken into account for local differentiation [Oosterhuis et al. 2004]. After a virtuosic structural optimization and a dramatic alteration of the geometry of Frank Gehry´s initial design, Jörg Schlaich, locally differentiated the material quality of nodes and rods by three material types, for the roof structure of the DG Bank in Berlin [Schlaich et al. 2001]. The Logo-roof of the New Trade Fair in Milan, also with an altered and optimized geometry, shows seven different beam heights, six different flange widths and four different web thicknesses [Schober et al. 2004]. For the case study, discussed in this paper, the shape of the surface should not be altered and the loads of the timber panels would not suggest any further differentiation, the authors focused on the local optimization of the steel nodes. Material thickness and the number of bolts (thus the weight of the nodes) were adjusted to the actual local stress. In contrary to the approach of Schlaich and Schober, the authors propose a workflow, which allows to optimize a structure bottom-up, without having to alter the initial architectural design. The structural system and the detailing should thus be developed before the global shape is specified. That way, the workflow is closer to that of Oosterhuis´ *Web of North Holland*. However, opposed to this concept, the author´s workflow is more generic, regarding the mesh topology, which it builds upon.

As the shape of the surface should not be altered and the loads of the timber panels would not suggest any futher differentiation, the authors focused on the local optimization of the steel nodes. Material thickness and the number of bolts (thus the length of the straps) were adjusted to the actual local stress.

2.3.1 Node design

As mentioned above, all nodes have four arms. Each arm is a strap with a specific number of bore holes and is aligned with the construction grid. They are all welded onto a disc of 200mm diameter. Not only the position of the strap on the disc is altered with each node, but also the inclination angle of the strap towards the disc. These deviations have been inevitable, as the flat timber panels obviously could not follow the surface normals of the skin surface. The simple shape of the rib is followed by an increase of complexity of the node. The planes of the ribs were found by the two nodal points, a rib connects, and the surface normal in one of the nodes. So in each node, there are two ribs, with edges aligned to the node´s surface normal, and two ribs, whose edges differ. To compensate for these deviations, the axis of the node is found in the middle of the intersection line of the none-aligned ribs and the aligned ones (Figure 6).

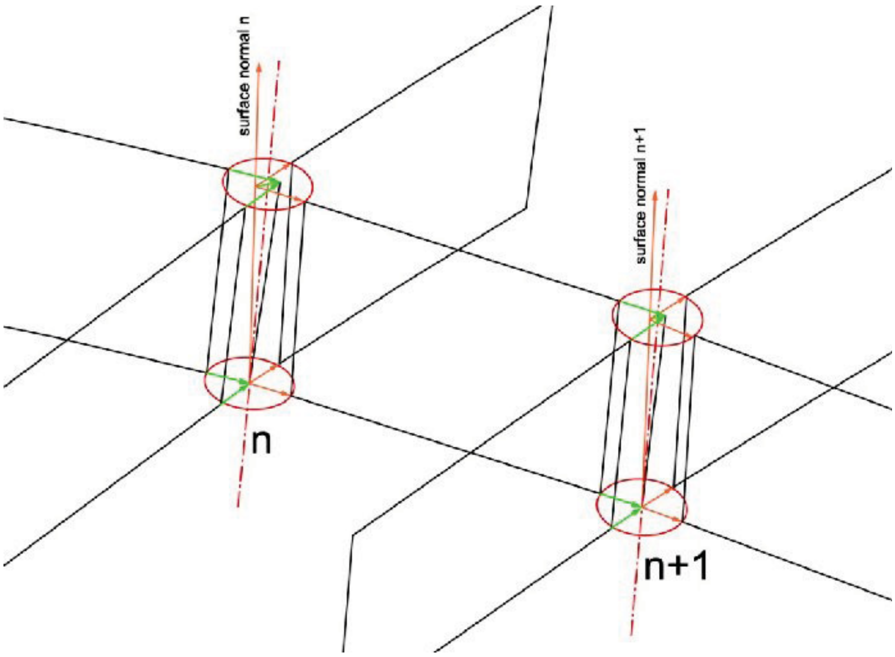

Fig. 6: Node geometry

At each node, one pair of panels follows the surface normal at that point (orange). A second line is found by intersecting the other pair (black). The node geometry builds upon a middle axis between these two lines (red).

From the data, given by the structural analysis, five strap types have been specified with a sheet thickness of 5mm and - for a few exceptions - 8mm (Figure 7). The disc thickness followed the thickness of the straps. The straps and the discs were further stiffened by a rod of 100mm diameter, 10mm resp. 18mm wall thickness and 80mm height. Figure 8 shows the analysis of a heavily loaded node. Those few extremes have been analyzed in detail.

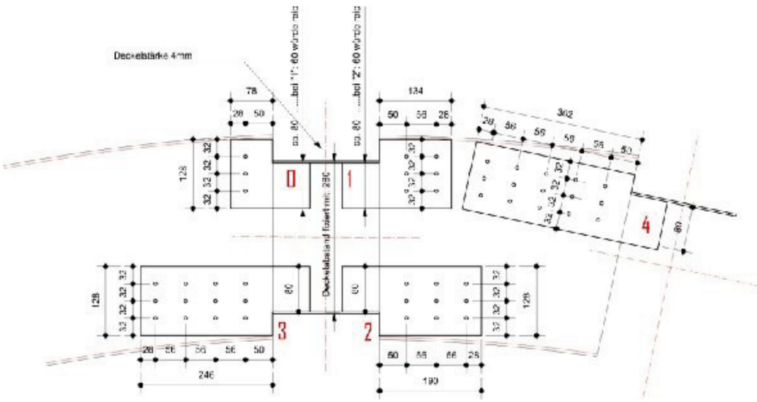

Fig. 7: strap design, five types that can be configured in any way to meet the local loads

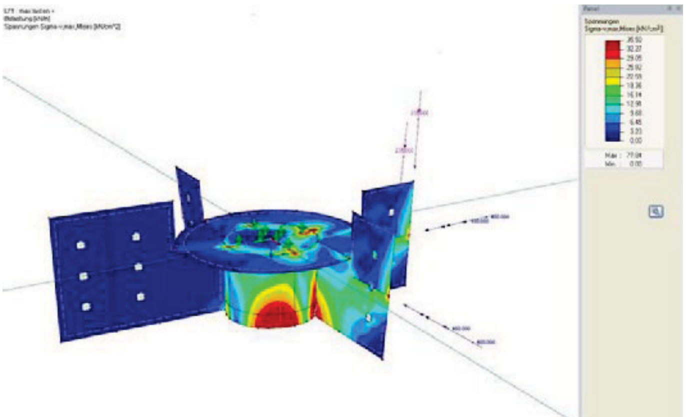

Fig. 8: Stress analysis of a node

Fig. 9: coded timber panels and different straps

A first concept showed double straps. After having built a mock-up, this concept has been abandoned, as it proved to complicate the assembling of the components. Instead, the timber panels would be doubled, by simply using the same cutting pattern and the steel node could be simplified subsequently (Figure 9). Further, as consequence of this test, the bolt size was increased from 6mm to 8mm and the number of bolts thus decreased. A further differentiation according to the force type transmitted by a bolt, once more reduced the total weight of the nodes by 30%: Bolts which transmit shear forces can be placed closer to the centre of the panel, reducing the length of the strap.

2.4 Script Workflow

In order to get quick results, Rhinoscript was chosen as the programming platform, a VB script based procedural programming language that comes with the common NURBS modelling package Rhinoceros 3D. When run, the script prompts for the input surface (i.e. the design) along with a set of constructional parameters such as the input surface, the segmentation and overall height of the construction, and the desired panel dimensions. Additionally, diverse structural measurements can be entered, e.g. the minimum length of welded seams. According to an FEM analysis that is run on the resulting supporting structure, a list of assignments of specific structural parts can be imported into the script that will be accounted for in a second run, thus resulting in the final construction (Fig. 10). Since the constructional geometry was defined to rely on two dimensional parts exclusively, these are appropriately labelled and finally moved to a common plane, where they are arranged in a way that they can easily be forwarded to CNC production without any further effort.

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198	O	3	1	3,50		1			
199	S	1	1	1,50	1				
199	W	2	1	2,50		1			
199	N	1	1	1,50	1				
199	O	2	1	2,50		1			
200	S	1	1	1,50	1				
200	W	1	1	1,50	1				
200	N	1	1	1,50	1				
200	O	1	1	1,50	1				
166	S	2	1	2,50		1			
166	W	7	1	7,50					
166	N	2	1	2,50		1			
166	O	6	1	6,50					
169	S	2	1	2,50		1			
169	W	6	1	6,50					
169	N	2	1	2,50		1			
169	O	6	1	6,50					
152	S	2	1	2,50		1			
152	W	5	1	5,50				1	
152	N	2	1	2,50		1			
152	O	6	1	6,50				1	

	Knotenindex	S	W	N	O
n	0	0	0	0	0
n	1	0	1	1	0
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n	4	0	1	0	1
n	5	0	1	1	1
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n	20	0	1	0	1
n	21	0	1	0	1
n	22	1	1	1	1
n	23	0	0	1	0
n	24	1	1	1	1
n	25	0	1	0	1
n	26	0	0	0	0

Fig. 10: Analysis of the FEM output (left chart) and thus derived node information to compose the nodes in Rhinoscript (right chart)

3. Outlook and Further Discussion

In the course of the development of this project, it was also discussed to develop the structural system according to a reciprocal grid or *Zollinger* structure. First it seemed improbable that such a construction can be adapted to a more radical free-form design. This kind of construction consists of ribs, which are two fields long, and shifted towards each other, so that in each joint two members meet in the center of a third one. The advantage of such a system is, that no flexural tension has to be transmitted by the joints. In a structural FEM analysis of such a system, applied to this project´s skin surface, this seemed to be promising. Yet, the design of the resulting node could not be found in time for this project. For the serpentine gallery, Cecil Balmond, Alvaro Siza and Eduardo Souto de Moura proposed a similar approach for a pavilion. Yet, the construction strategy has been less generic, as the relatively flat geometry allowed for more or less parallel ribs [Sakamoto et al. 2007].

4. Conclusion

Free-form design could much more contribute to the architectural quality of every-day design tasks, as it augments the design options within strict zoning regulations. The approach described by the authors is applicable for small design practices, as it can be based on readily available CAD modeling software and trivial geometric specifications. The described construction method has been carried out by local companies at adequate cost (total construction cost has been below EUR 110.000,- : that involves 90 m2 roof and a new story of appr. 70 m2). The workflow shifts responsibility and liability from companies and contractors to the architects and their consultants, as the success of the construction is completely depending on the data produced by the planning team. This has to be reflected in the planner´s fees. For the client the workflow dramatically increases the certainty about cost, as all elements are known before the start of building process. The parametric, generic nature of this concept allows for changes in the very last minute before construction starts, as has happened with this project (Fig. 11). Such changes are nearly effortless for the planners. All construction data is updated and formatted within a few hours.

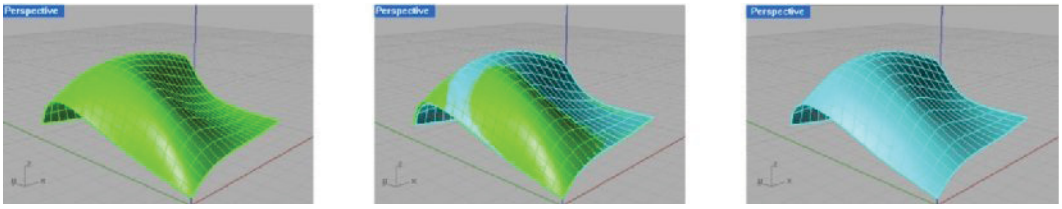

Fig. 11: last-minute change of the roof shape

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5.2 Acknowledgement

Dipl.-Ing. Peter Bauer. Werkraum ZT GmbH, 1060 Wien, Austria, creatively accompanied the project as a structural engineer. He helped to develop the connection details and to set up the workflow. Furthermore, he always was a perfect adviser, when were hit by the non-virtual side of reality.

Dipl.-Ing. Heinz Schmiedhofer, Zirkusgasse 39/34, 1020 Wien, Austria, wrote and edited endless lines of script. He, too, contributed to the setup of the workflow, patiently following all the turns and detours of the project.

MULTI DIMENSIONAL INFORMATION MANAGEMENT PLATFORM FOR WIRELESS EMBEDDED MONITORING OF BUILDING PERFORMANCE DATA

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ABSTRACT: *In terms of energy efficiency, buildings possess significant potential for energy and energy related CO_2 emissions savings since buildings account for 25-30% of total energy related CO_2 emissions. As buildings account for almost 40 % of the total energy usage in Europe the European Commission undertakes much effort to reduce the energy consumption of buildings emphasizing on energy rating to inform and stimulate subsequent building renovation activities. Wireless monitoring and optimisation of buildings' energy consumption is of central importance for the renovation and energy-efficient operation of buildings since it allows the identification and correction of inefficient energy usage. Current studies show that improved building control systems can contribute to the reduction of energy-consumption of buildings by 5 to 30%. In addition, it is often faster and less costly to automate building systems than it is to insulate building shells. Thus, flexible and easy to handle monitoring control technologies are essential. In order to address these issues in this paper, we offer a multi dimensional information management platform backed by a new integrated data aggregation layer coupled with open and extensible information exchange facilities to support tool interoperability. It offers e-services for energy monitoring and control using data warehouse, data mining and web service technologies.*

KEYWORDS: *Energy Efficient Buildings, Integrated and Intelligent Control, Data Warehouse Technology, Building Information Modeling.*

1. Introduction

Europe's objective under the Kyoto Protocol and Copenhagen Summit is a reduction in the level of GHG emissions while also decreasing the current dependence on imported energy due to the fact that the EU currently imports 82% of its oil and 57% of its gas, making it the world's leading importer of these fuels. The EU can have little influence on external energy markets and energy supply but can influence domestic energy demand. One possible solution to both the above problems is to reduce energy consumption by improving energy efficiency. Energy consumption for buildings-related services accounts for approximately one third of total EU energy consumption. It is obvious that, with initiatives in this area, significant energy savings can be achieved, thus helping to attain objectives on climate change and security of supply.

Current residential and office buildings provide a significant contribution to total energy consumption and CO_2 emissions. Reports by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Department of Energy note that buildings account for 25-30% of total energy related CO_2 emissions (Price et al. 2006). International Energy Agency (IEA) set Eco-Design Strategies in order to increase the energy efficiency of buildings. Among these strategies home automation systems are the most cost effective solution without going under heavy refurbishments (Gökçe 2010). Several case studies suggest that energy savings between 15%-40% can be made in buildings by closer monitoring and supervision of energy-usage and monitoring of related data (Salsbury & Diamond 2000).

Apart from meaningful building insulation measures, the only means of achieving marked improvements in the energy efficiency of buildings is to make use of efficient building automation technologies which comprises automatic control, monitoring and optimisation (VDMA 2008). According to European standard *"EN 15232 Energy Performance of Buildings-Impact of Building Automation"* building operation systems can, depending on building type and equipment standard, produce the following potential savings of energy: restaurants 31%, hotels 25%, offices 39%, shopping centres 49%, hospitals 18%, schools/universities 34% and residential 27% (DIN EN 2007). Also, it is often faster and less costly to automate building systems than it is to insulate building shells. Thus, flexible and easy to handle monitoring and control technologies are essential. Presently, many sophisticated building services systems are available for facilities management. However, their focus on energy performance rating of buildings is at best sporadic, often comprising an ad-hoc combination of off-the-shelf building management systems (BMS) with some extensions. Such systems provide many problems to building owners with regard to interoperability. The optimisation of these systems for energy management adds another layer of complexity to the design and management procedures. It requires analysing the system, developing new interfaces, replacing devices, newly adjusting and optimising parameters and so on.

In order to address these issues a multi dimensional information management platform for wireless embedded monitoring of building performance is developed. The system extracts sensor data from building management systems and from a wireless sensor network. Collected sensor/meter data is stored in the operational data store (ODS) for data cleansing and redundancy check processes. This pre-processed data is loaded to the fact data section of the data warehouse system via an Extraction, Transformation and Loading (ETL) tool. Simultaneously, data gathered from the building information model e.g. CAD tool and the performance framework specification tool (O'Donnell 2009) is loaded to the dimensional data section of the data warehouse. Loaded fact data and dimensional data is aggregated with regards to different stakeholder requirements in the data warehouse system and presented through specific Graphical User Interfaces.

2. Multi Dimensional Monitoring, Analysis and Optimisation Process

In this section, a building performance monitoring, analysis and optimisation process is introduced which creates a basis for the developed multi dimensional information management platform for wireless embedded monitoring of building performance data.

A basic monitoring system should aim to: (a) state current consumption. (b) Compare current consumption with historical data and benchmarks. (c) Identify trends and patterns.

The multi dimensional monitoring, analysis and optimisation process establish a standard for energy performance and CO_2 emissions through conversion factors for each energy consuming object e.g. zone, individual, organisation and building system. In order to achieve energy savings, the standard performance of the each energy consuming object needs to be improved. The level of improvement in performance is determined through comparison of the standard performance with the benchmark performance values underlined by several regulations e.g. CIBSE Guide F Benchmarks (Gökçe 2010). The proposed multi dimensional monitoring, analysis and optimisation process is depicted in Figure 1.

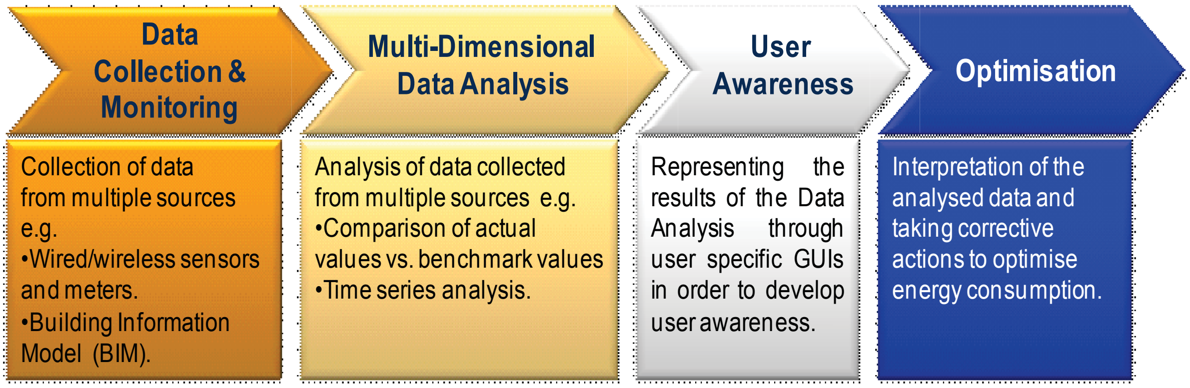

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Fig. 1: Multi Dimensional Monitoring, Analysis and Optimisation Process (Gökçe 2010).

The process is broken down into the following four steps:

Data Collection: Energy consumption data is usually obtained from meter readings and energy consumption bills. This conventional process slows down the data collection process. Recent improvements in the sensor and meter technology offer cost effective and quick solutions to collect building related data. Therefore, it is recommended to use wireless/wired sensors and meters to collect both consumption and comfort related data.

In order to define, categorise and classify the data collected from sensing devices, building related information such as architectural layout, material information, HVAC systems, sensing device placement, occupant related information etc. is required. BIM technology offers the opportunity to get all building related information.

Multi-Dimensional Data Analysis: Exponentially increasing data sources and data points make it impossible to analyse data manually. Modern Data Warehouse technologies provide multi-dimensional data analysis and decision support functionalities by using the huge amounts of data sets.

The main objectives of data analysis are to: (a) Measure progress towards benchmarks. (b) Indicate when performance has been good and should be replicated. (c) Evaluate the significance of changes in performance. (d) Determine where/when corrective action is required.

A range of analysis methods are used for assessing building performance and the three main methods are shown below. With these methods, actual energy consumption is compared with the following (CIBSE 2004):

1. ***League tables:*** based on a range of factors e.g. highest CO^2/m^2, highest electricity $kW.h/m^2$ etc. league tables can be used to identify the worst performing buildings in a large estate.
2. ***Benchmarks:*** a comparison is made with a standard consumption benchmark to establish how the building compares with typical and best practice buildings. These are specified as performance indicators usually in kg CO_2/m^2 per year for fossil fuel and electricity in $kW.h/m^2$.
3. ***Performance lines:*** these lines (e.g. variation of heating consumption with degree-days) make it possible to check whether the services continue to function in relation to key variables.

4. ***Historical data:*** a comparison with a previous measurement to ascertain whether previously adopted energy efficiency measures have been effective, and to identify the need for further improvement.

User Awareness: Analysed data is represented to the different stakeholders e.g. building owner, facilities manager, occupant/tenant and technical staff through specific Graphical User Interfaces (GUI) in order to develop user awareness.

Optimisation: Data represented through GUIs, interpreted and necessary corrective actions should be completed to optimise building energy consumption.

In the following section the holistic multi-dimensional information management system will be introduced with its components.

3. The Holistic Multi-Dimensional Information Management System

Recent advancements in building technologies and building control strategies coupled with the introduction of new building codes have contributed to the improvement of poor energy performance in commercial and residential buildings.

A holistic approach for building performance monitoring requires consistent and simultaneous access to the data and information extracted from different sources. Energy efficiency reports and trend analysis should be accessible to energy managers also, other stakeholders but this is often not the case (Piette 2005).

In order to address these issues a methodology leading to a system appropriate to process and analyse building performance data named as "Holistic Multi- Dimensional Information Management System" (Figure 2) is developed to store, integrate, analyse complex data sets from multiple data and information sources such as wired/wireless sensing devices (sensors and meters) and BIM tools. Data collected from the sensing devices is classified and categorised by the information collected from BIM tools and used for performing multi-dimensional analysis of building performance data to support decision-making process of the end users (Gökçe 2010).

The system extracts sensor data from building management systems and from a wireless sensor network. Collected sensor/meter data is stored in the operational data store (ODS) for data cleansing and redundancy check processes. This pre-processed data is loaded to the fact data section of the data warehouse system via an Extraction, Transformation and Loading (ETL) tool. Simultaneously, data gathered from the building information model e.g. CAD tool is loaded to the dimensional data section of the data warehouse. Loaded fact data and dimensional data is aggregated concerning different stakeholder requirements in the data warehouse system and presented through specific Graphical User Interfaces (GUIs).

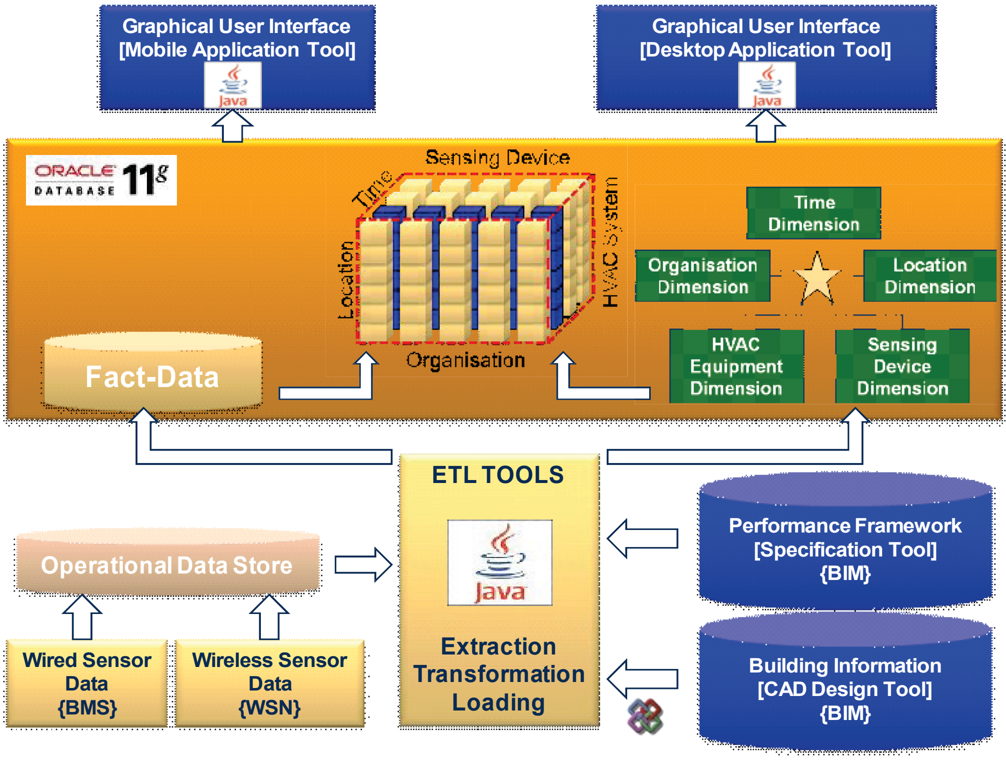

Fig. 2: Architecture for Holistic Multi-Dimensional Information Management System for Building Performance Data (Gökçe 2010).

The system consists of three integrated main components, which will be explained in the following sections. These components are: (1) Extraction, Transformation, Loading (ETL) Layer (2) Data Warehouse Core and (3) Information Representation Layer.

3.1 Extraction, Transformation, Loading (ETL) Layer

Data need to be loaded to the data warehouse core regularly. To do this, data from one or more operational systems needs to be extracted and loaded into the warehouse. The processes of extracting data from source systems and bringing it into the data warehouse are commonly called ETL, which stands for Extraction, Transformation, and Loading (Loney 2004).

In the data warehouse, raw operational data is transformed into a warehouse deliverable fit for user query and consumption (Kimball 2002). This is executed by a set of processes called ETL processes, which involves: (1) Extracting data from multiple sources such as wired/wireless sensor/meter readings and BIM tools. (2) Transforming it to fit data warehouse requirements which might be inconsistent with the outside data sources, e.g., data type inconsistencies and (3) Loading it to the data warehouse core.

The advantages of efficient and consistent data warehouses make ETL very important as the way data actually gets loaded. For the developed system, the ETL tool is used to populate the fact data table, which stores long-term dynamic data such as measurement streams. In addition, the ETL tool is used to populate Dimensional Tables, which store persistent data extracted from BIM tools (Gökçe 2010).

The sensor is the most basic component of the developed system and the accuracy and the signal quality needs to be specified at design. The deployment of wireless sensors is usually undertaken following an ad hoc procedure. Connectivity between nodes is obtained through a “try it and see” approach. Although such an ad hoc approach may work in a small environment it relies heavily on the designer’s experience, is time consuming and is unlikely to provide an optimal solution in large scenarios. In order to assist the deployment of the developed system based on wireless sensors and actuators a scalable WSN design optimization algorithm and methodology integrated in a software tool to support designers and system integrators when undertaking the difficult task of WSN deployment for wireless building energy management (Guinard et al. 2009).

Sensing device dimension consists of sensing device information such as wired/wireless sensors and meters. This defines and categorizes the sensing device related data for multi dimensional analysis purposes. Virtual deployment and placing of these sensors is done automatically by a tool called "WSN Design Optimisation Tool" developed by CIT AWS group within the scope of BuildWise research project (BuildWise 2010). This tool contains sensing device information required by the DW.

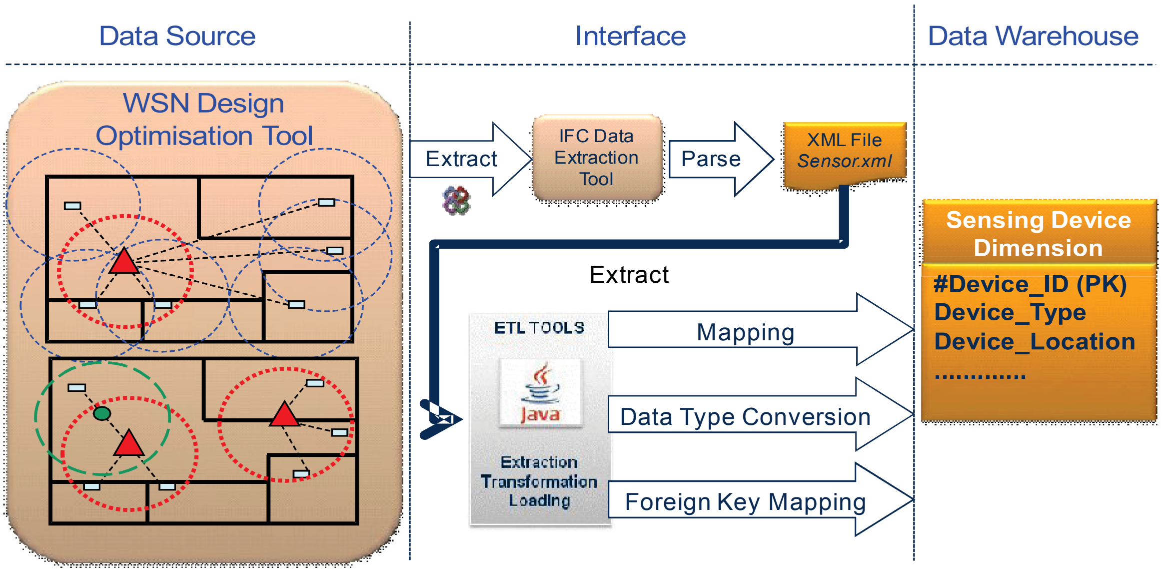

Fig. 3: The ETL Process for the Sensing_Device_Dimension Table (Gökçe 2010).

Figure 3 depicts the developed system's ETL process to populate the Sensing_Device_Dimension table. This process involves (a) Extracting the sensor placement information from the WSN Design Optimization Tool which is developed by CIT AWS Group (Mc Gibney et al. 2008) by using IFC (Industry Foundation Classes) data extraction tool. (b) Parsing the extracted data to a file in XML format, e.g., Sensor.xml. (c) Extracting the data from the XML file. (d) Transforming the extracted data by proving necessary mappings, data type conversions and foreign key associations. (e) Loading the pre-processed data to the data warehouse's Sensing_ Device _Dimension table.

3.2 Data Warehouse Core

The data warehouse stores summarized information instead of operational data. This summarized information is time-variant and provides effective answers to queries such as "Energy consumption of a particular room in a particular building when the outside temperature is 21°C."

The aim of the data warehouse component of the system is to: (1) Collect dynamic data (streaming data) which is data that is asynchronously changed as further updates to the data become available, from different sources such as wired/wireless sensors and meters. (2) Map the dynamic data with the persistent data, which is data that is infrequently accessed and not likely to be modified, extracted from BIM tools to define and categorize dynamic data. (3)Perform multi-dimensional data aggregation to support decision-making process (Gökçe 2010).

Components of the Data Warehouse Core are briefly described as;

Operational Data Store: The Operational Data Store (ODS) is a database designed to integrate current valued subject oriented, volatile and real time data from multiple sources such as building management system and wireless sensor/meter network. An ODS is usually designed to contain low level or atomic (indivisible) data (e.g. measurements) with limited history that is captured "real time" or "near real time" as opposed to the much greater volumes of data stored in the data warehouse generally on a less frequent basis.

Fact Data: Fact data is the main repository for long-term storage of dynamic data. A fact table is the primary table in a dimensional model where the numerical performance measurements of the business are stored (Kimball 2008). A measurement is taken at the intersection of all the dimensions (e.g. Time, Location, and Organisation). This list of dimensions defines the grain of the fact table and depicts the scope of the measurement. A row in a fact table corresponds to a measurement.

Dimensional Data: As explained above the Fact Data table contains the data, and the Dimensional Data identifies each tuple (row) in that data. A dimension table consists of tuples of attributes of the dimension. Dimension attributes are very crucial in the data warehouse. These serve as the primary source of query constraints, groupings, and report labels. For example, a user request stating "Minimum temperature of the offices which are occupied by Energy Systems Engineering Department staff in the Engineering Building for the last 3 months" is only achieved with time, location, sensing device and organisation dimension attributes.

Aggregated Data: Aggregated data is the decision support level of the multi-dimensional data warehouse core. Every data warehouse contains pre-calculated and pre-stored aggregated data. In the context of the work, sensed raw data collected from wired/wireless sensors and meters populates the Fact Data table of the data warehouse. Fact data becomes meaningful when it is associated with the dimensional data and provides the end user the means to create data cubes. Figure 4 depicts an example of a data cube with regard to time, sensing device and organisation dimensions.

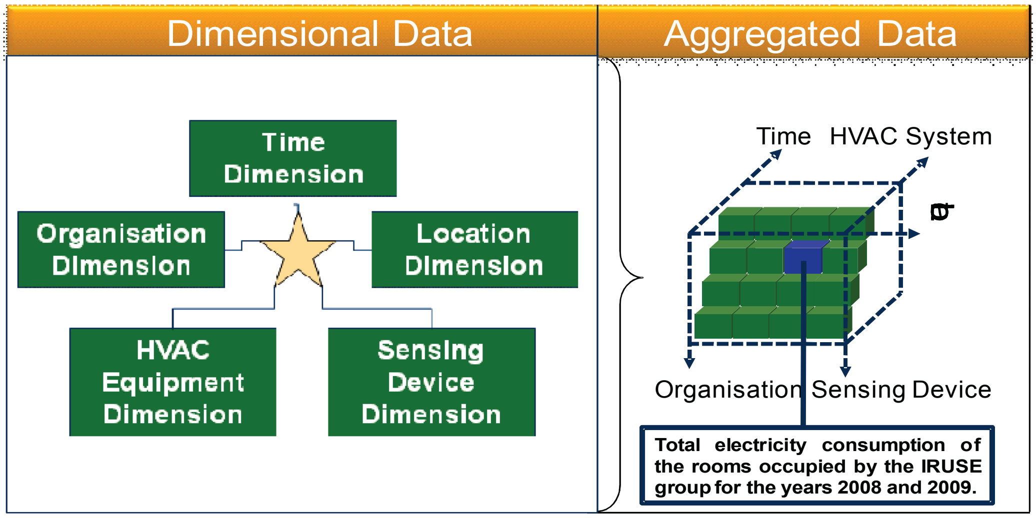

Fig. 4: Aggregated Data and Data Cube (Gökçe 2010).

The SQL statement and the output for the cube illustrated in Figure 4 is given below. In order to create this cube, Time, Sensing_Device and Organisation dimensions are required.

```sql
SELECT O.GROUP, T.CAL_YEAR_NUMBER, L.SPACE, SUM(F.VALUE) FROM ORGANISATION_DIMENSION O, TIME_DIMENSION T,LOCATION_DIMENSION L, SENSING_DEVICE_DIMENSION S, FACT_DATA F
WHERE T.TIME_ID=F.TIME_ID
AND S.DEVICE_ID=F.DEVICE_ID
AND O.ORGANISATION_ID=F.ORGANISATION_ID
AND O.ORGANISATION LIKE 'IRUSE%'
AND T.YEAR BETWEEN 2008 AND 2009
AND S.DEVICE_TYPE='ELECTRICITY METER'
GROUP BY CUBE (L.SPACE, T.CAL_YEAR_NUMBER);
```

Space	Cal_Year_Number	Value
LG04	2007	2482
LG04	2008	2628
LG04	All	5110
G07	2007	4428.5
G07	2008	4689
G07	All	9117.5
All	2007	6910.5
All	2008	7317
All	All	14228

Fig. 5: Example of a 2-Dimensional Cube Output (Gökçe 2010).

The output of this SQL statement creates a 2-Dimensional cube (Fig. 5). The semantics of the CUBE operator are that it first aggregates over all the ‹select list› attributes in the GROUP BY clause as in a standard GROUP BY. Then it UNIONs in each super-aggregate of the global cube– substituting ALL for the aggregation columns.

3.3 Information Representation Layer

The common goal of the graphical user interfaces is to represent the building performance information to the end users (stakeholders) concerning their roles and functions. The aim of the proposed system's information representation section is designing and implementing user friendly Graphical User Interfaces (GUI). In order to achieve this, a Java based interface is developed which enables end users easy querying without dealing with complex SQL statements. In addition, this GUI is capable of representing query results both in graphical format and/or in tabular format regarding to stakeholder preferences.

Stakeholders include any person or organisation that may be affected by the success or failure of the software (Marinilli 2006). Four principle stakeholders identified for the developed system. Their data requirements and roles are described below (Gökçe 2010):

- ***Building Owner:*** (a) Reviews the overall energy consumption and CO_2 emissions of facilities. (b) Reviews the energy consumption and CO_2 emissions of a particular organisation, occupant or zone (c) Generates consumption bills and audits the costs of facilities.
- ***Facilities Manager:*** (a) Monitors and analyses the building performance data with regards to particular zone (Location_Dimension), organisation/occupant (Organisation_Dimension), building system (HVAC_Equipment_Dimension) and/or time interval (Time_Dimension). (b) Maintains optimum occupant comfort level.
- ***Occupant/Tenant:*** (a) Monitors relevant energy consumption and CO_2 emissions. (b) Views real time energy consumption costs. (c) Requests user comfort.
- ***Building Technician:*** (a) Compares actual and intended performance of building systems (HVAC Systems) in order to perform preventive maintenance activities.

Figure 6 depicts a Graphical User Interface developed for Facilities Manager. Onsite building technicians require support to perform maintenance activities in an effective manner as identified during the preventive maintenance planning phase. Preventive maintenance is a series of scheduled inspection routines on building plants. In this case failures can be seen before a failure may occur. In order to achieve critical support for members of the FM team, a mobile device application is developed. Figure 6.a depicts the GUI developed for the performance based preventive maintenance system. This GUI retrieves compares and presents actual and intended performance of the selected building systems. This enables building technicians to monitor performance losses of the particular system which causes more energy consumption and may lead to more costly maintenance activities. The GUI consists of Location Selection, Building Systems Selection and Time Selection sections.

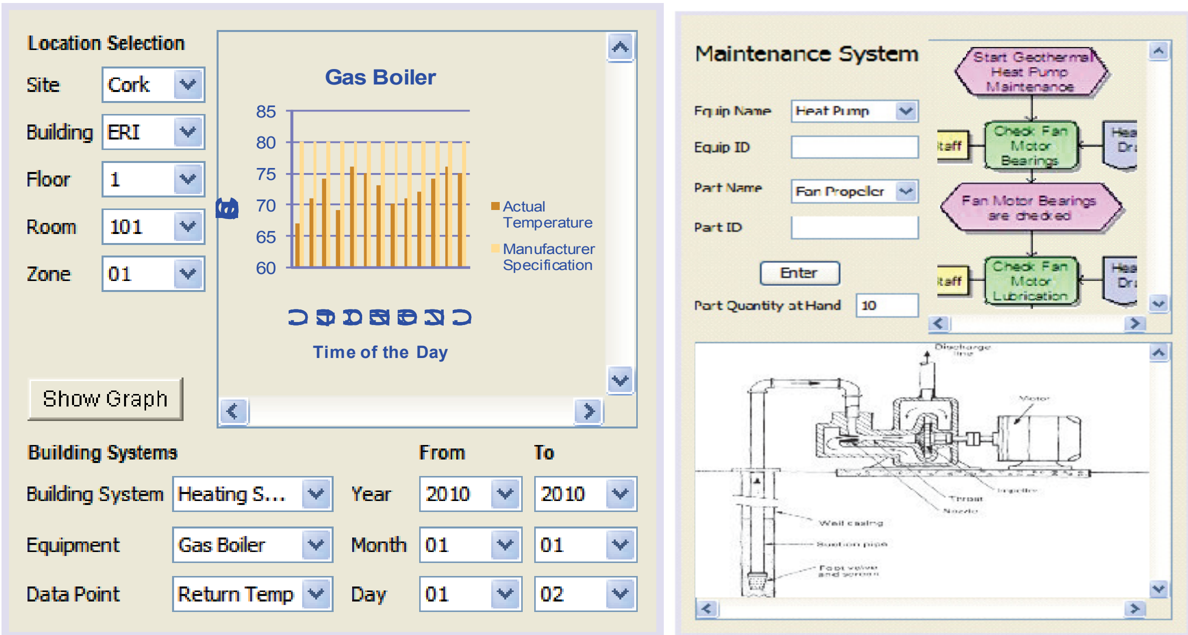

Fig. 6: Building Technician GUIs (left a, right b) (Gökçe 2010).

In addition to the performance monitoring GUI, a more comprehensive GUI to complement the maintenance activities is also developed.

The scenario for this GUI implementation starts with performance monitoring which enables end-user to detect performance problems prior to specific building equipment. In our case a decline in the heat output and an increase in electricity consumption of the geothermal heat pump are detected. Secondly, the responsible maintenance technician who is specified with ARIS Model[2] is informed to diagnose the problem. Finally, maintenance staff performs the required maintenance activities that are specified with ARIS EPC.

Figure 6.b depicts the maintenance prototype user interface. This GUI retrieves and presents inventory data, the ARIS process model for specified maintenance tasks and equipment schematics. Onsite maintenance staff is better equipped to track spare part inventory and to see availability of required spare parts, perform exact maintenance activities as defined with ARIS EPC model and visualise technical drawings for the specific equipments.

4. Conclusions

In this research, a multi dimensional information management platform for wireless embedded monitoring of building performance data was introduced. Initially, the methodology named as; Multi Dimensional

[2] ARIS Architecture of Integrated Systems is developed by IDS Prof. Scheer GmbH as a business process engineering tool. ARIS as a modelling method provides semi-conceptual methods of describing process-organisational issues.

Monitoring, Analysis and Optimisation Process which act as a backbone for the developed system was introduced. This was followed by the description of the Holistic Multi-Dimensional Information Management System with its components: Extraction, Transformation and Loading (ETL) tool, Data Warehouse core and Information Representation tools. The purpose of the developed system is to store, integrate, analyse complex data sets from multiple data and information sources such as wired/wireless sensing devices (sensors and meters) and BIM tools. Data collected from the sensing devices is classified and categorised by the information extracted from the BIM tools and aggregated for performing multi-dimensional analysis of building performance data to support decision making processes of the different stakeholders through specifically developed GUIs. The developed system is open to further expansions. Since the system stores all building related information, it offers a high potential for building performance monitoring and multi-dimensional analysis as a powerful tool for data aggregation. This aggregated data can be used and be further developed for more advanced data analysis techniques like Knowledge Discovery (KDD) and Data Mining.

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BaSim$_{Ba}$ – A MODEL KIT FOR PROCESS SIMULATION IN CONSTRUCTION

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ABSTRACT: *This paper presents an approach on the development of a domain-independent toolbox to model construction processes. Based on the processes detected by Ailland during the production of bridge curbs in bridge construction, the determining sub-processes will be captured and the suitable process modules will be developed. The previous findings on the relationship between the individual sub-processes and their corresponding dependencies of required resources serve as the basis for an extendable toolbox, which will enable it to model process flows in construction engineering easily. This toolbox is to be implemented in a standard notation, such as UML, SYSML or EPC. This will guarantee independence to defined simulation tools. Afterwards it is the goal to integrate the developed building blocks as a library to a suitable simulation tool to enable a simulation of the developed process models. The aim of such a simulation is, to optimize the process flows with regard to different criteria, such as the total construction time of the project, the total cost and the risk management. A special focus here is the view on the various construction methods and their determining factors in relation to a simulation. For this reason, the individual processes are assigned by their decisive variables to different process classes. Finally, a library of modules will be available, which allows the user to create process flows for construction procedures quick and easily.*

KEYWORDS: *simulation, modeling, process modeling, unified modeling language*

1. Introduction

In times of strong PC computing systems and highly developed modeling and simulation tools, it is clear that by the use of these mechanisms attempts are made to optimize processes in various fields and to map their sequence of activities computer-aided. This relates among many other areas of production, and logistics processes also to the construction industry, which is characterized by a high degree of individuality and the unique characteristic of the buildings (Kugler 2008). Performing a simulation of a production or manufacturing process in advance of construction, which provides information about the anticipated costs and timing makes it possible to take direct influence to the process chain during the planning phase. Simulation can thus support the development of different schedules, avoid bottlenecks, improve the total duration of the project and reduce costs. Particularly in relation to the scheduling of the construction processes the use of simulation techniques is no longer novelty. However, the actual construction processes and in particular the various construction methods are not considered sufficiently. While the pure visualization of planned construction processes and their simulation by using the underlying real data allow meaningful conclusions about the scheduling and the expected costs, the optimization of the construction process based on individual construction processes and with respect to the different simulation targets, such as construction costs, construction time and quality, is not yet supported.

The aim of this paper is to discuss the possibilities of creating a model kit, with which construction processes based on different construction methods can be modeled and afterwards optimized with respect to specific objectives in a simulation environment. Based on the knowledge of construction management a context-independent library of process modules should be created, which can serve as foundation for the modeling of complex construction processes.

2. State of the Art

Voigtmann (Voigtmann 2010) recalls that simulation of construction processes has recently got a lot of attention by the researchers. This includes extensive research projects such as ForBAU (Günthner 2010) and Mefisto (Beißert 2010 and Scherer 2010), dealing among others with the identification of critical processes on construction sites. The approach of identifying these processes is different in each of these projects. Especially in regard to the representation of the construction projects in models, several methods exist, thus, for example models are created by using Petri nets (Franz 1998) or software-specific modeling environments. Based on these models different simulation tools can be used afterwards and can be aligned to different simulation goals. The creation of a standardized library of model components, which is regardless of software-specific requirements of a selected simulation tool, has been difficult until now, as each modeling tool requires individual process modules.

3. Creation of the Model Kit

The basis for the development of a model kit is to determine the relevant construction processes, which due to the variable construction methods provide a corresponding modeling potential and therefore have a substantial influence on the considered simulation objectives. Based on the identified processes these parameters could be determined afterwards, which allows variability and thus is interesting for the simulation of the building processes in advance of the actual construction. Here answers to the process time, process costs, the resources required and the quality of the final product can be expected.

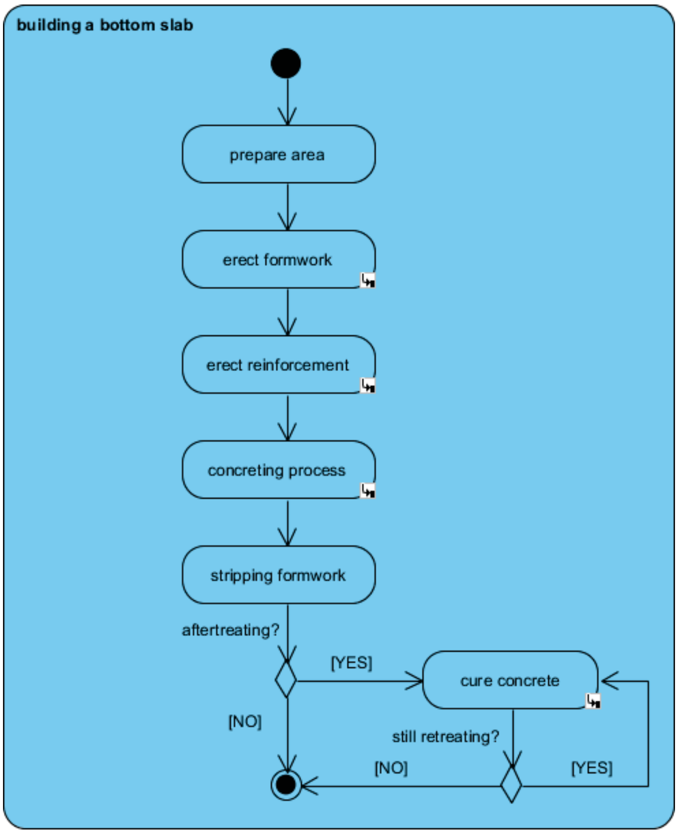

Fig. 1: process chain for building a bottom slab

Besides the optimization of relevant parameters, the relations between the individual processes play a significant role, too, particularly the pre- and post-conditions of each process. For example, there are conditions for the process "concreting process" (Fig. 1) that must be fulfilled in order to allow starting the "stripping" process. So the stripping and other downstream processes are usually only possible if the concrete has reached a certain degree of curing. This pre- and post-conditions have to be identified completely, too.

Therefore the determined relationships between the various processes of a construction sequence are, in addition to the simulation parameters, relevant criteria of variability in the simulation model. Hence it is possible to optimize the process chain itself by using the pre- and post-conditions of the individual process steps. This is possible for example by varying the order of the process flow or by parallel execution of individual process steps.

The model kit thus contains at last a series of prefabricated process elements, with which relevant construction processes could be mapped and parameterized. On the basis of the stored parameters (time, cost, resources, etc.), process relationships and basic logics, construction processes can now be optimized in view to various criteria.

In order not to limit in advance the application fields to certain modeling tools, the model kit should be done in a standard notation, such as the Unified Modeling Language (UML), event-driven process chain (EPC) or modeling methods that combine the advantages of both notations (Dandl 1999). In this way it is possible to define an universally designed model kit. It guarantees independence of the restrictions and requirements of a single software tool by using suitable interfaces and provides to various simulation tools. In addition to this, the using of a domain-independent and standardized notation allows furthermore the use of a variety of tools and existing solutions in the field of process modeling, also for other industries.

4. Design of the Model Kit

The individual process elements of the model kit (Fig. 1) can either be lined to relevant parameters, which represent the real performance, and/or they are broken down into detailed sub-processes, which can be assigned to appropriate process classes. The allocation is based on process-relevant parameters and can vary depending on the allocation criteria. It is proposed that the assignment should be based on the criteria, which probably has the most impact on the outcome target that should be optimized. For the differentiation of the processes three classes are formed (Fig. 2), which differ with respect to this criterion.

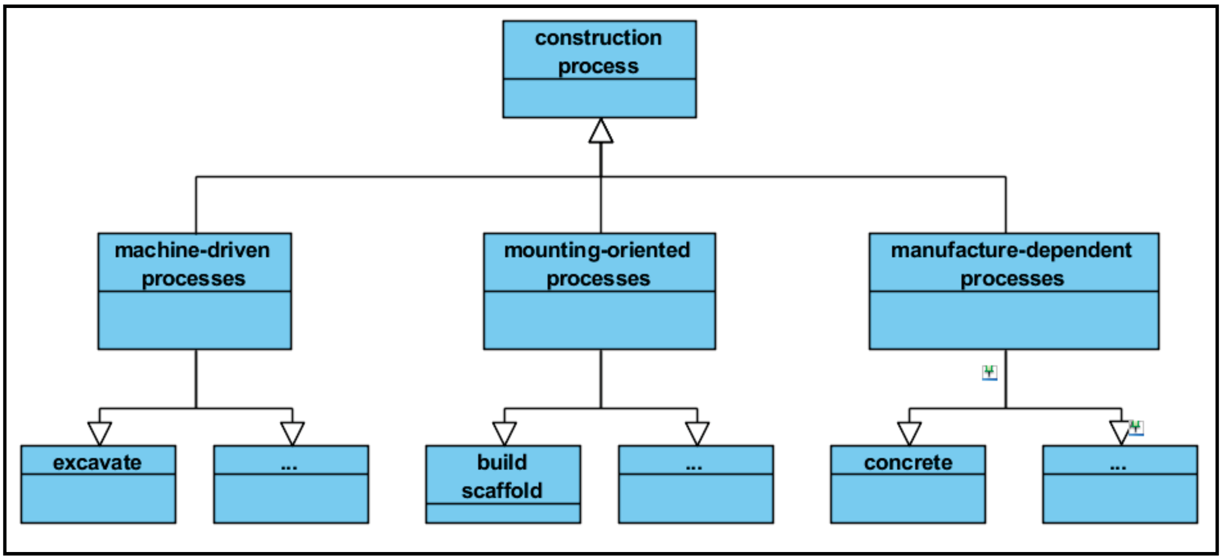

Fig. 2: Class diagram to visualize the process hierarchy

The duration of the process, the cost and the quality of the result of "machine-driven processes" are mainly influenced by the used machines and their performance. At "mounting-oriented processes" there are mainly logistical conditions in the macro and micro ranges that affect the outcomes. Especially to the assembly on specified plans the micro-logistical installations count, such as the plugging of windows, including the insertion of the sealing rubber. In the last category of "manufacture-dependent processes", the outcome is mainly influenced by the technical skills of the workers involved.

Such a hierarchical specialization of individual construction processes offers the advantage of process-relevant parameters that can be passed down from one hierarchy level to the next, which means a simplification, especially in terms to a later implementation of the model kit into appropriate modeling and simulation tools. The number of hierarchical levels of process modules can be expanded arbitrarily. Thus the process class scaffolding (Fig. 2) can also be divided into relevant sub-processes, to permit a more detailed modeling of the individual process steps.

5. Building a Model Kit for the Construction Process of Bridge Curbs

To investigate the possibilities of creating such a model kit, it is necessary to limit this to a well-determined and limited example. For this purpose the construction of a bridge especially the production of bridge curbs was considered.

Before starting extensive investigations were conducted at the Bauhaus-Universität Weimar, which have analyzed in detail the production process of this reinforced concrete element. (Ailland 2010b) The decision to choose manufacturing bridge curbs as a suitable process example for the simulation of a construction process has several reasons, according to Ailland. First, it is a good manageable, almost independent, self-contained component, at which the essential manufacturing processes of bridge building can be well observed (Ailland 2010a, p. 167), and it allows to transfer the findings also to other processes in the construction industry. Secondly, the construction process can easily be varied so that there is an adequate opportunity for the later simulation model to optimize more realistic variants. (Ailland 2010a, p. 167)

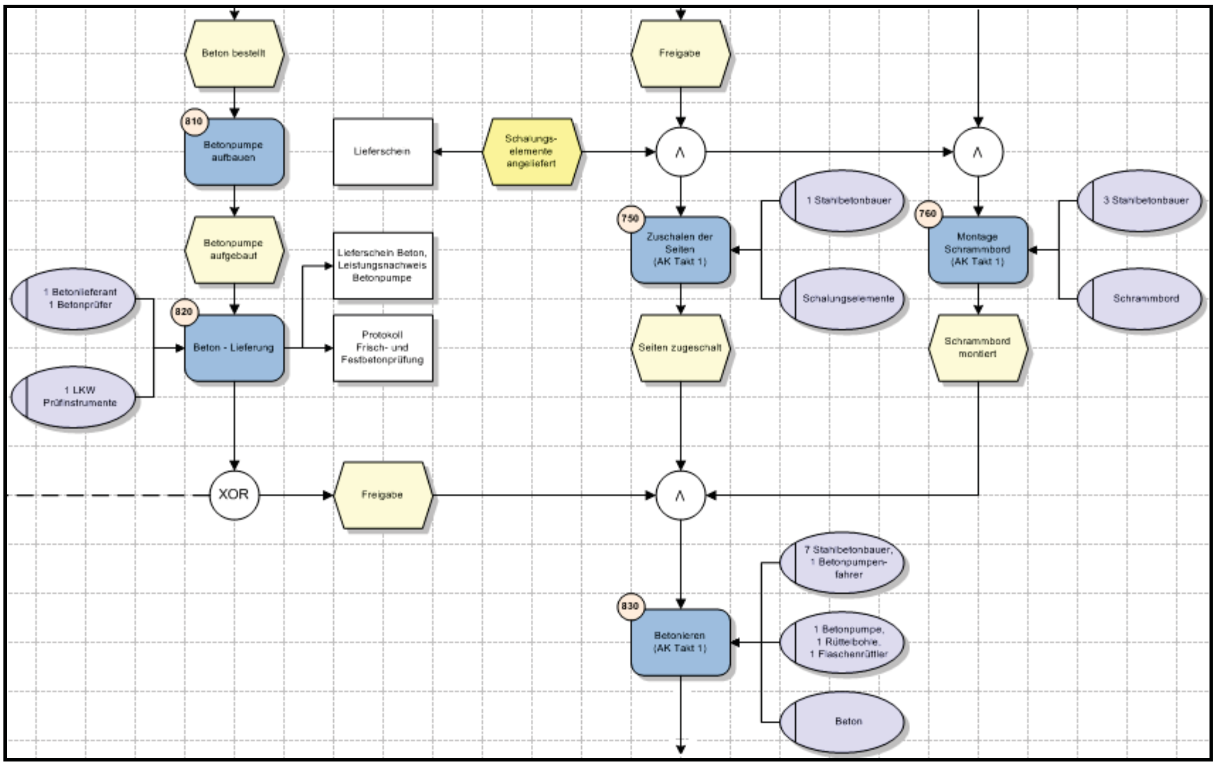

Fig. 3: Extract from Ailland's EPC for the production of bridge curbs

During the research of the manufacturing process of bridge curbs of several bridge projects, which show a considerable variety in terms of complexity and dependencies, all relevant process steps have been monitored, characterized and documented. (Ailand 2010b, p. 3253) One of the results of this data collection was a detailed process description, which was visualized with the help of event-driven process chains (EPC), and which also visualizes the dependencies of each process step to preceding process steps, and to events and resources needed (Fig. 3).

5.1 Data acquisition and database

Basis for the schematic process flow developed by Ailland was given by a series of field studies, by which it could be determined, what information was needed to depict and optimize the entire construction process in a simulation model. (Ailland 2010a, p. 165) During these field studies carried, all daily events, occurrences and the corresponding execution durations as well as the equipment used and personnel and material capacities were identified and recorded. (Ailland 2010a, S. 167) Moreover, also the dependencies between different recorded operations were identified.

Result of this data acquisition is an exact definition of the construction process of the production of bridge curbs, which in the following is to serve as the basis for the creation of a process-specific model kit. Pursuant to this modular system for the present example process an implementation of the model kit into a suitable simulation tool will take place.

5.2 Processes

Because the process flow determined by Ailland is very detailed and therefore very extensive, is necessary to summarize the individual sub-processes together into basic modules before implementing them in a simulation tool. This grouping will inevitably lead to a reduction and idealisation of the reality which in turn leads to an inaccurate representation of the real construction process. Such a reduction is unfortunately inevitable, but should be kept to a minimum to nevertheless allow reliable simulation results. (Kugler 2008)

Yet, a compression of the sub-processes into manageable modules is required, particularly in regard to a desired implementation of the overall process. For this reason, the process chain developed by Ailland was simplified and limited to the main sub-processes and their individual dependencies and required resources. The resulting simplified process chain later forms the basis for the extraction of the individual building blocks.

Fig. 4 shows the cutout of the detailed event-driven process chain developed by Ailland shown in Fig. 3. In this representation especially the upstream sub-processes of individual

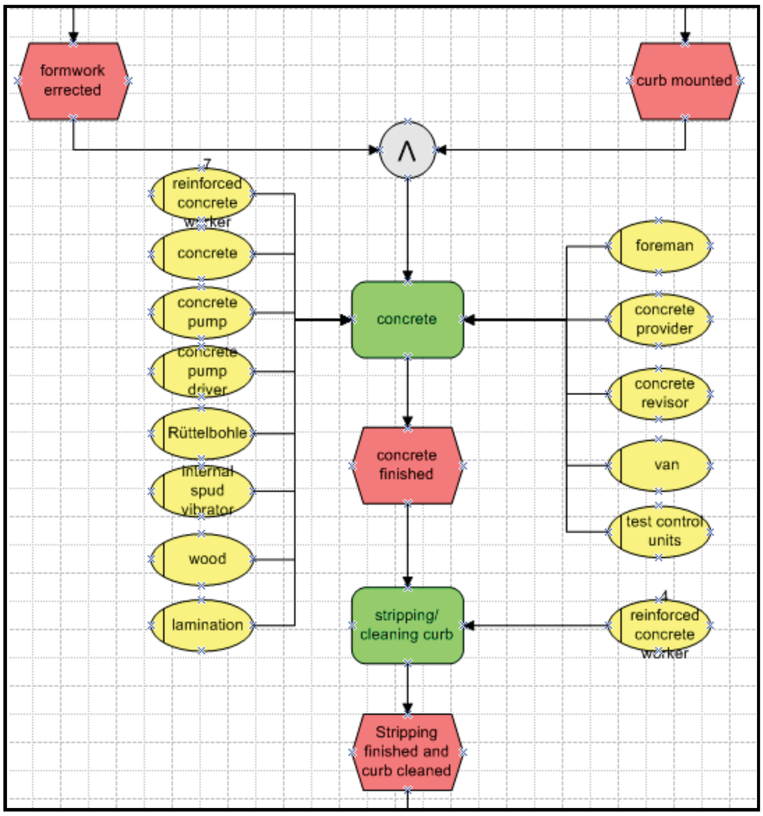

Fig. 4: Detail of summarized EPC for the production of bridge curbs

process steps, e.g. the construction of the concrete pump and the delivery of concrete, have been summarized in an overall process (here: concreting).

The processes identified this way can now be assigned to the process classes illustrated in Fig. 2. The allocation to the classes is based on the reference value, which determines the target size to be optimized. This classification into appropriate categories is particularly necessary in view of the subsequent implementation in a suitable simulation tool, since the individual processes differ significantly in terms of the parameters required for simulation.

Thus, the machine-driven processes are determined by parameters and dependencies, which can be precisely captured and described numerically: for example, the performance of a concrete pump during the process of concreting.

As already mentioned manufacture-dependent processes, however, are determined by the technical abilities of the individual workers. These skills and the influencing factors associated with these skills (e.g. weather, psychological and physical factors) cannot be transferred into precise numerical data. It shows, that one cannot always make a specific allocation to one of these three process classes, since some of the process components include either machine-driven, as well as mounting-oriented and manufacture-dependent processes as sub processes. This is solved by either determining the one class, which is governing a mixed process, or by subdividing the corresponding processes into clearly identifiable sub-processes.

An allocation of the processes to the given classes is especially required with respect to the parameterization of the designed model and in regard to the updating of each parameter in the course of a day-to-day data acquisition during the construction work, because the classes are different in terms of the variability of their parameters.

5.3 The acquisition of the day-to-day data

The determination of the individual process modules forms the basis for the creation of a simulation model for a specific construction project. However, the simulation of the model depends on the available data for the actual construction work, which can be adopted by appropriate proceedings and entered into the simulation. The already available simulation tools are increasingly in use and they make it possible to model a proposed construction project and to simulate the building process beforehand. But especially civil engineering is often exposed to unexpected changes, which require deviations from the originally simulated building process. (Ailland 2010b)

To simulate these changes it is necessary to provide a corresponding data base, which allows to present the current construction progress and the changed framework conditions, e.g. the availability of resources or deviating time schedules. The modules, which should be developed, should provide the opportunity to handle timely acquired data and to represent in this way the simulation for the current progress.

As with any other construction projects also the bridge building and thus the production of bridge curbs is affected by such variable dependencies and changing conditions. These changes must be recorded to perform an update of the simulation model. In this way it is possible to adapt the results of previous simulations to the variable conditions and to ensure a representation of the current construction progress in the simulation model. This also allows a repeated simulation of the model based on actual data, which in turn gives to more realistic results and thereby leads to more reliable statements regarding the further construction process.

A determination of the data, which is necessary for an acquisition of the actual building progress for the process of bridge curbs production has already been performed by Ailland. Respective possibilities of data acquisition have already been presented. (Ailland 2010b) In relation to the development of the process modules, it is also necessary to design appropriate interfaces to update the simulation parameters and to integrate these interfaces during the implementation of the toolbox into a simulation tool.

6. Conclusion and Outlook

This paper shows how a software- and context-independent model kit for process modules in construction engineering can be developed, with which construction processes, based on different construction methods, can be modeled and afterwards with respect to specific objectives can be simulated and optimized. In a first step, all necessary data is recorded for a chosen sample process (construction of bridge curbs) and displayed in form of an event-driven process chain by Ailland. Based on this process chain, the individual sub-processes are combined to complex units. These identified components can then be assigned to the appropriate process classes, based on the basis of their determining factors.

In a next step, the identified processes including their interdependencies will be mapped into a domain-independent and standardized notation (e.g. UML or EPC) to enable an implementation of the resulting model kit for the production of bridge curbs into different simulation tools. In a subsequent step, this kit will be implemented in a selected simulation tool. The input parameters for the simulation are recorded by corresponding data acquisition during the construction phase. The simulation model is thus kept up to date and therewith it allows a flexible simulation of the entire process, while also considering changing process conditions and actual resource availability.

Moreover, it will be possible to consider additional dependencies. This is especially interesting in view of the availability of working space on the construction site (Elamahdi 2010) and with regard to the influence of other hazards like weather on the construction progress (Le 2010). In addition to the development of a toolbox for the modeling and simulation of specific construction projects, the central aspect of the work presented is in particular the development of suitable concepts for day-to-day data acquisition on the construction site and the consequent updating of the simulation model. Moreover it is also possible to build up a decision rules-driven knowledge system, which supports the selection of the appropriate processes out of the library and in dependence of the recorded day-to-day data.

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INTEGRATING AND VISUALIZING MAINTENANCE AND REPAIR WORK ORDERS IN BIM: LESSONS LEARNED FROM A PROTOTYPE

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ABSTRACT: *Facilities are designed and constructed with the use of various types of information and by different parties of different specialization. Facility managers on the other hand, need to gather and access all such information during operations in order to manage and maintain facilities. The efficiency of the operations and maintenance (O&M) process is expected to be highly increased with the availability of an integrated digital database of facility information that can provide easy access to relevant information through the component of interest itself. A Building Information Model (BIM) has a capability to provide a 3D visual database that can store links to the relevant information to facility components and systems. In current practice, integrated digital facility information that can enable analysis of facility performance is not generally available. Therefore, facility operators do not always have data-driven insights to make informed decisions and action plans. In order to identify problems in the facility, it is necessary to compare performance history of components; correspondingly spatial clusters of maintenance and repair work can be used for visually investigating the performance. Also, temporal analysis is needed for trending, which can help displaying and identifying abnormalities and finding causes of problems. Commonly, a work order (WO) is used to store the information about maintenance and repair work in a facility. However, most of the time, WO information is stored in paper or digital databases and not investigated together with other facility information (e.g., space, component, system, etc.) since information sources/databases are not linked and analyses capabilities are limited by the type of information stored in each individual system. The authors aim to address the need for storing and visualizing WO information in a 3D digital facility information database that can enable spatio-temporal analysis for understanding patterns of maintenance and repair tasks in a facility to support proactive maintenance decisions.*

KEYWORDS: *BIM, Work Orders, Maintenance and Repair, Information integration, Visualization, Spatio-temporal Queries*

1. Introduction

Facilities are designed and constructed with the use of various types of information and by different parties of different specialization. Facility managers on the other hand, need to gather and access all such information during operations in order to manage and maintain facilities. Hence, facility operators often have to go through several documents to find information necessary to support their daily tasks and decisions. This constitutes to lost time during operations for searching for and accessing data when needed (Fallon and Palmer 2007). Moreover, most of the information items are represented in different structures and formats as they are generated by different parties during the design and construction phases. Hence, dispersed and unformatted facility information needs to be integrated for supporting informed decisions about operations and maintenance. The efficiency of the operations and maintenance (O&M) process is expected increase with the availability of an integrated digital database of facility information that can provide easy access to relevant information directly linked to the component of interest. A Building Information Model (BIM) has a capability to provide a 3D visual database that can store facility information and manage links to the additional relevant information to facility components and systems.

Furthermore, visualizing facility information can provide additional benefits to facility managers. Visualizing information can lead to new insights, more efficient decision making and improve problem-solving capabilities (Dull and Tegarden 1999; Gershon et al. 1998). In a preliminary user study, we explored the possible benefits of visualization of work order information integrated with a 3D model. The users included facilities management experts from a CMMS software company, and they were asked to assess whether displaying work order information using different techniques such as color maps, symbols and text provides further insights. The users indicated that such visualization made it easier to identify abnormal conditions of the building components. The effectiveness of how information is visualized differs depending on the inputted data types (e.g., qualitative, ordinal, 1D, 2D) and the purposes of users, such as whether they are observing a historical trend, observing a distribution, or performing a comparison (Keim 2002; Lohse 1991). Therefore, in this paper we aim to identify different techniques and explore their effectiveness in visualizing work order information and trends.

The next section describes the problem in more detail. It is followed by sections discussing our approach, the lessons learned from our implementation, and the conclusions.

2. Problem

As mentioned in the introduction, facility operators need integrated information about the facilities to support their daily tasks and decisions. However in current practice, integrated digital facility information that can enable analysis of facility performance is not generally available. Therefore, facility operators do not always have data-driven insights to make informed decisions and action plans. This mostly affects maintenance and repair (M&R) practices; since there is no reliable information to predict breakdowns and proactively maintain the facility, it ends up being repaired only reactively or based on scheduled maintenance. However, reacting to failures is very costly and shortens the service life of facilities (Mobley 2008; Sullivan et al. 2004). In order to enable understanding of how the building is deteriorating and planning proactive maintenance and repairs, there is a need to analyze information from daily M&R work (Akcamete et al. 2010). Commonly, a work order (WO) is used to store the information about maintenance and repair work in a facility. Yet, most of the time WO information is stored in paper or digital databases (i.e. Computerized Maintenance Management Systems) and not investigated together with other facility information (e.g., space, component, system, etc.). The analyses required by facilities managers are performed in an ad-hoc manner since information sources/databases are not linked and analyses capabilities are limited by the type of information stored in each individual system. In order to identify problems in the facility, it is necessary to compare performance history of components; correspondingly spatial clusters of maintenance and repair work can be used for visually investigating the performance. Also, temporal analysis is needed for trending, which can help in displaying and identifying abnormalities and finding causes of problems. The authors aim to address the need for storing WO information in a 3D digital facility information database that can enable spatio-temporal analysis for understanding patterns of maintenance and repair tasks in a facility to support proactive maintenance decisions.

In order to illustrate the challenges in the current practice and discuss possible improvements with our approach we describe a motivating use case. In this case, a facility manager wants to investigate the cause of *hot/cold call* WOs in the facility. First, he wants to find the spaces that have the most *hot/cold call* WOs in the past three months. However, when he goes through the WOs, he realizes that the space names for the WOs are not captured consistently, as different abbreviations are used for the same spaces and no space names are entered for several of the cases. He had to spend additional time to manually fix the naming of the spaces by using the drawings and spreadsheets with room tags and consulting with the technicians who created the WOs. After manually correcting the data, he realizes not all of the WOs have the location of the repair that has been made; rather they only capture the space where the call comes from. Since this information is missing, he continues with the space information he currently has and calculates the number of *hot/cold call* WOs in each space. As a result, he identifies that room 121 has the most *hot/cold calls* in the past three months. To investigate the cause of these WOs, he searches other WOs that have taken place in the same space, room 121. He finds that there are several WOs that requested re-calibration of the temperature sensor of the thermostat in this space. In order to determine whether there is a correlation between the occurrence of *hot/cold calls* WOs and temperature *sensor re-calibration* WOs, he wants to compare the trend of the frequency of these two types of WOs in room 121. If the *hot/cold call* WOs have the similar trend with the *sensor re-calibration* WOs, the malfunctioning sensor is likely to be the cause of the problem. By manually charting all the *hot/cold call* and *sensor re-calibration* WOs within the last three months that he could associate with this space, he sees the correlation and the drastic increase in the frequency of *sensor re-calibration* WOs. Therefore, he generates a proactive WO for inspection and repair or replacement of the sensor. Without the availability of WO records with the space and component information, it is not possible for the facility manager to investigate the cause of the problems in the manner described. Automated comparison and trend visualization capabilities can actually facilitate this task.

This use case highlights the need for integrating the WOs with building context information and investigating the maintenance and repair history for identifying reoccurring problems and potential breakdowns. It shows the need for having the spatial information captured in the WOs, so as to look into spaces, rooms, or different areas of the facility separately, see the clusters, and compare the differences. Current practice does not ensure consistently capturing space or room information for each WO, and BIM can facilitate this. Since all the spaces have their unique names and IDs in a BIM, this can enable following the naming conventions easily by automated linkage of spaces to WOs. As a result, spatial analysis of WOs can be performed. Furthermore, since every component in BIM knows which space it is located in, it is possible to capture the location of the repair that has been made for each WO only by entering the component that is fixed. Once space and component information are stored in the WOs, it is also possible to perform further analysis within BIM for identifying root cause of the problems or reoccurring WOs by utilizing the information about the topological relationships of the systems.

3. Approach

In this paper, we describe and illustrate an approach for storing and visualizing WO information in a digital facility information database. We intend to visualize the WOs spatially by leveraging BIM, and to enable spatio-temporal analysis for understanding patterns of WOs in a facility. We developed a proof-of-concept prototype that can retrieve the facility information stored in a BIM, visualize the facility in 3D and link WO information to this model. Our prototype utilizes a standard representation of the Building Information Model stored in Industry Foundation Classes (IFC) format and visualizes the facility information within an IFC viewer. For this purpose, we utilized an open source IFC tool and viewer, named Open IFC Tools (Tulke et al. 2010), and built our WO integration and visualization prototype on top of this IFC viewer. This section describes our approach in detail by describing the automated linkage of work orders and BIM, and querying and visualization of the linked information.

3.1 Investigation of information items contained in work orders

The current industry practice for communicating and storing information about the maintenance and repairs is generating work orders. Usually, the information stored in a work order is the only feedback about problems occurring in a facility and the remedies taken for resolving them. Therefore, capturing all the relevant information in WOs is very important for tracking the maintenance, repairs, and changes done in a facility. In order to understand types of information currently captured and maintained in work orders, we conducted case studies using the work order records from a university building and a hospital building. As a result of these case studies, we realized that there are differences in the types of information that are stored in different organizations' databases. Also we have seen many examples of missing information since the templates used to define the necessary information from maintenance and repairs are not always filled out completely by the field workers. From these work orders, we identified information items that are necessary to store a WO history and to integrate and visualize the history with BIM. Table 1 provides two typical examples of WOs and information that needs to be captured associated with them. All of the information in this table is represented in our prototype and work order data from the case studies is used for the integration.

Table 1 depicts two example work orders: WO1 involves replacing a leaky pipe; and WO2 involves repairing a supply fan in an air-handling unit (AHU). The types of information captured in the WOs includes, *Name* (or short description) and *Description*, *Request and Finish Date, Type* of the work, *Location* of the work, *Shop* that performs the work, *Components* that are maintained or repaired, *Labor hours* spent for the work, and *Labor, Material, and Total Costs* for the work. WO1 is performed in Room 105 from May 20th to 26th involves repair of a pipe due to a water leak and replacement of a section of the dry wall that has to be removed so as to access and replace the pipe section. A plumber and a carpenter work on this repair for 13 hours at a labor cost of $530.18 and a total material cost of $55. WO2 is a repair of the supply fan belt in mechanical room A11, which is reported as a problem on June 1st and is repaired by June 3rd. The electrician fixes the belt-relaxation problem in 6.5 hours, charges $162.50 and had to uses $198.99 worth of material for the repair.

Table 1: Example work orders depicting the information in relation to problems and work performed

	Work order 1 (WO1)	**Work order 2 (WO2)**
Name	Replace a leaky pipe	Repair the supply fan in an AHU
Request Date	05/20/2011	06/01/2011
Finish Date	05/26/2011	06/03/2011

Type	Replace	Repair
Location	Room 105	Mechanical room A11
Component(s)	Pipe, dry wall	Supply fan
Shop/Trade	Plumber, Carpenter	Electrician
Description	Pipe's leaky section was replaced and the wall cut to access the pipe was replaced.	The supply fan in AHU 2 has a belt-relaxation fault and was repaired.
Labor Hour	13:00	6:30
Labor Cost	$530.18	$162.50
Material Cost	$55.00	$198.99
Total Cost	$585.18	$361.49

These example WOs will also be used while explaining the details of our approach for the automated linkage of a BIM and work orders in the following section.

3.2 Automated linkage of BIM and work orders

Linking two information sources is done by identifying the information items that are represented by both sources and mapping the values of the common information items in a consistent way (Heimbigner and McLeod 1985; Halfawy 2009). There are two common information items in both the BIM and work orders: location of the work order and components that are associated with the work order. As shown in Table 1, among the information items contained in a work order, *Location* and *Components* indicate the spatial information of the work order. For instance, in Table 1, *WO 1* describes the task of replacing a leaking pipe. A facility manager needs to find and inspect the spaces that are below the leaking area to find out whether they are affected or not. These spaces can be found using the *Location* information of *WO 1*, which indicates that the leakage took place in *Room 105*. In current practice, field workers either look at the floor plan of the building or go to the site to find which spaces are below *Room 105*. Similarly, *WO 2* describes the task of repairing the supply fan of an AHU. Since repairing the supply fan affects the normal performance of the entire AHU and all spaces that are served by it, a facility manager needs to find out what are the affected spaces and warn the occupants about the repair work. According to the information item *Components* of the *WO 2*, that facility manager can search in a mechanical drawing of the building to find out which spaces are associated with the supply fan.

Since the information in the *Location* and *Components* fields of a work order are also represented in BIM, the work orders can be linked with BIM using these two information items. In BIM, entities such as the spaces, walls, ducts and equipment have global unique identity (GUID) (buildingSMART 2010). Using a GUID-based approach ensures that different spaces and components do not have repeated names, and therefore ensures the consistent naming convention. However, currently standard naming conventions are not always followed while filling the work orders, as discussed in the motivating use case. Therefore, to ensure the consistency of the linkage between BIM and work order information, in this research we implemented the linkage between work order and BIM by associating the work order with the ID of spaces and building components in BIM. Figure 1 shows the UML diagram of the instances of work orders and building elements. This diagram shows the simplified information of the work order and building elements to illustrate the linkage between work orders and a BIM.

In this UML diagram, the WorkOrderPackage contains the instances of class WorkOrder, which stores the information of each work order. The BIMPackage contains the instances of classes in BIM. In this simplified example, only the instances that are directly related to the two work orders are described. The two instances of WorkOrder class contain the information that is described in Table 1. The difference between the contents in the table and diagram is that instead of storing the name of the associated spaces and building elements, the work order instances only store their GUID. If the information about the spaces and components is needed, it can be queried from BIM directly since the GUID is unchangeable for the entities in BIM. For example, using the GUID of the Components in WO 1, the associated components "Water pipe 1201" and "Dry wall 011" can be accessed from BIM and the relevant information can be retrieved.

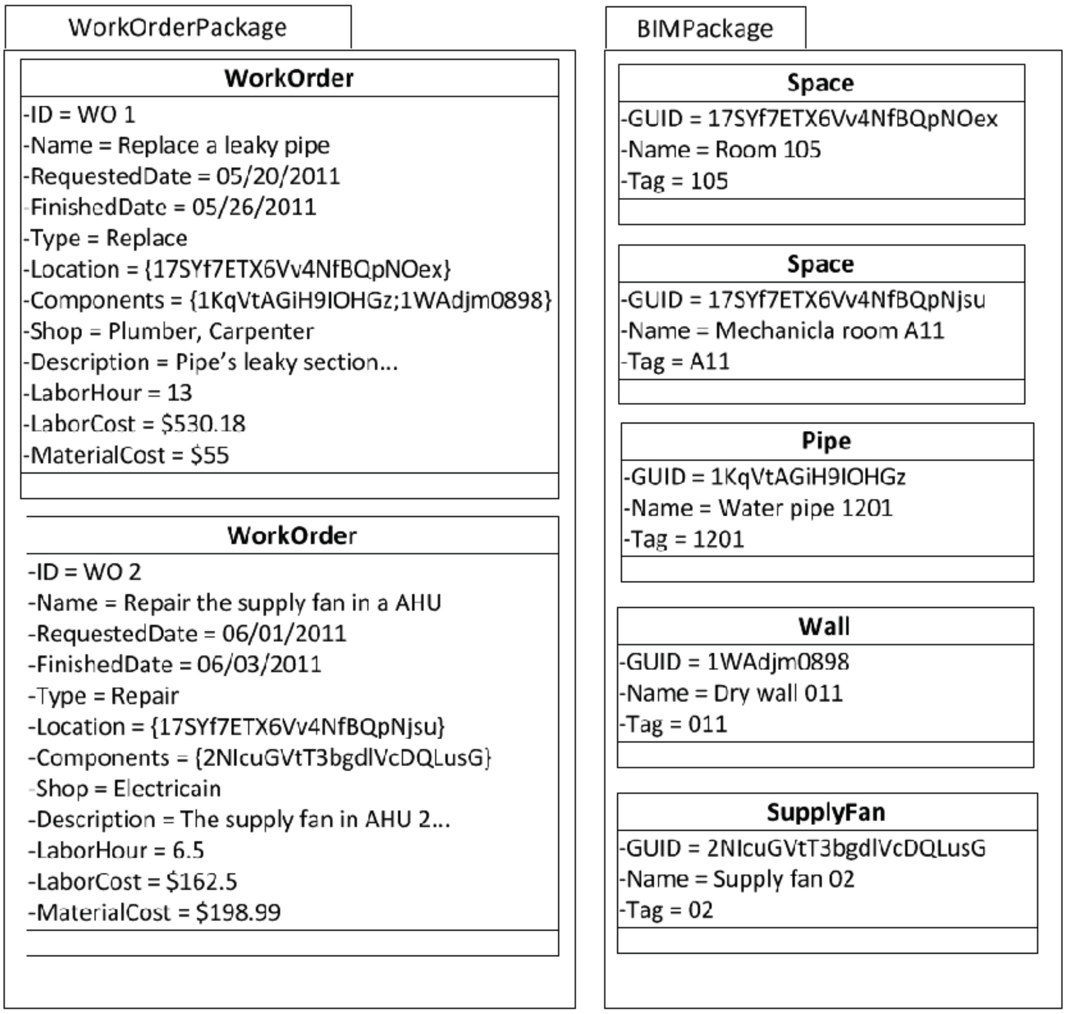


Fig. 1: UML diagram of the instances of work orders and building elements for illustrating the implemented linkage between work order and BIM

The following sections will discuss how this linkage approach can enable the spatial visualization and query of work order information in BIM.

3.3 Querying and visualization of work order information in 3D BIM

Visualizing all the work orders at the same time is not very useful as it is difficult to comprehend all this information at a time. Therefore, there is a need to query this WO information in order to visualize only the work orders retrieved as a result of the query. Therefore, our approach allows users to query the WO information linked with BIM, based on different information categories stored in the WOs (such as type, cost, and shop) and building components related information (such as type, location). Moreover, by leveraging the BIM, spatial and temporal patterns of WOs can be queried and displayed to get further insights about the previous WOs in the facility.

As discussed in the motivating use case, the objective of linking work orders with BIM is to enable spatial and temporal analysis of work order records. Spatial analysis aims to compare the number or cost of maintenance tasks that have been done in different parts of the building. For example, if a supply fan has more repair work orders than other ones in the same floor, it suggests that this supply fan may be aged and a replacement may be cheaper than enduring frequent repair. Temporal analysis aims to show the trend of work order history so that the abnormal condition of the building components can be identified. For instance, if the monthly count of hot calls from one space rises from two to eight, it suggests that the temperature control system that serves that space may have faults and needs to be inspected.

There are three main approaches for showing data (Tufte and Howard 1983):

a) *Sentences*, which directly describes the data in plain text,

b) *Text or numeric tables*, which list the data in columns and rows, and

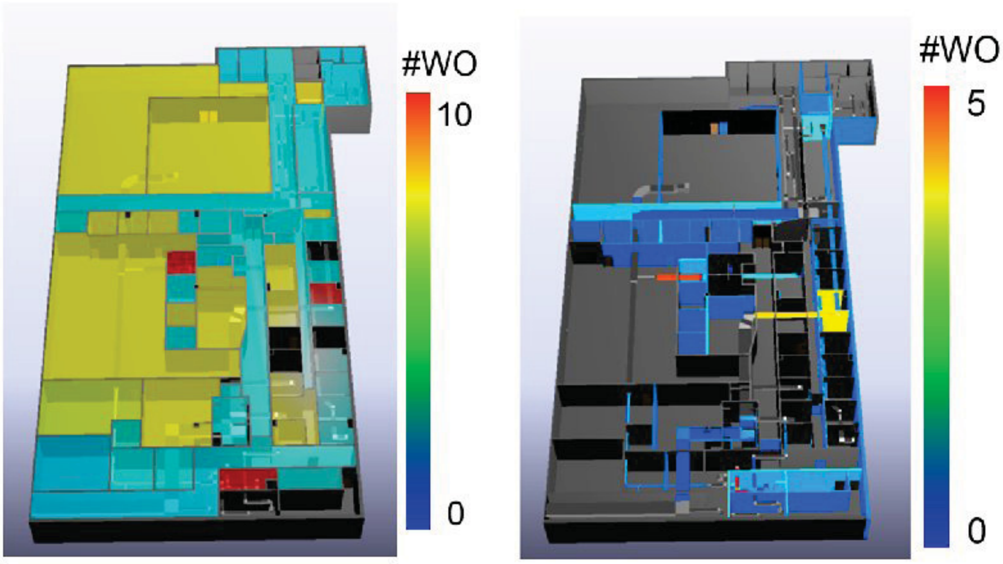
c) *Graphics*, which visualize data in figures.

These three approaches have different advantages and disadvantages based on the different purposes for showing the data. For example, tables have the advantage when showing quantitative data, while graphs perform better at showing qualitative information, such as increasing or decreasing trend and comparison of multiple data sets. Since the objective of this research is to show trends and comparisons, we explored several of the graphical visualization approaches.

The objective of visualizing data comparison is to enable the identification of abnormal behavior of maintenance history on certain spaces or components. For example, if most of the spaces have two repair work orders per month and one space has nine repair work orders, the cause of these work orders in this room is possibly atypical. Hence, attention should be paid to this abnormality, so that the problem can be detected and fixed at an early stage before it results in more problems and waste. Data comparison enables people to identify clusters of data sets that have a qualitative difference. According to the requirements of the user, the cluster can be categorized into different number of levels, as in a rating scale. For example, to compare the monthly cost of work orders in each space in five cost range levels, a facility manager can divide the maximum monthly cost by five and categorize the spaces into each group. In this research, we used a color map to visualize the comparison of number of, or cost of, work orders for each space or component. Figure 2 shows two examples of using a color map to visualize the amount of work orders that are related to the spaces and components in the BIM.

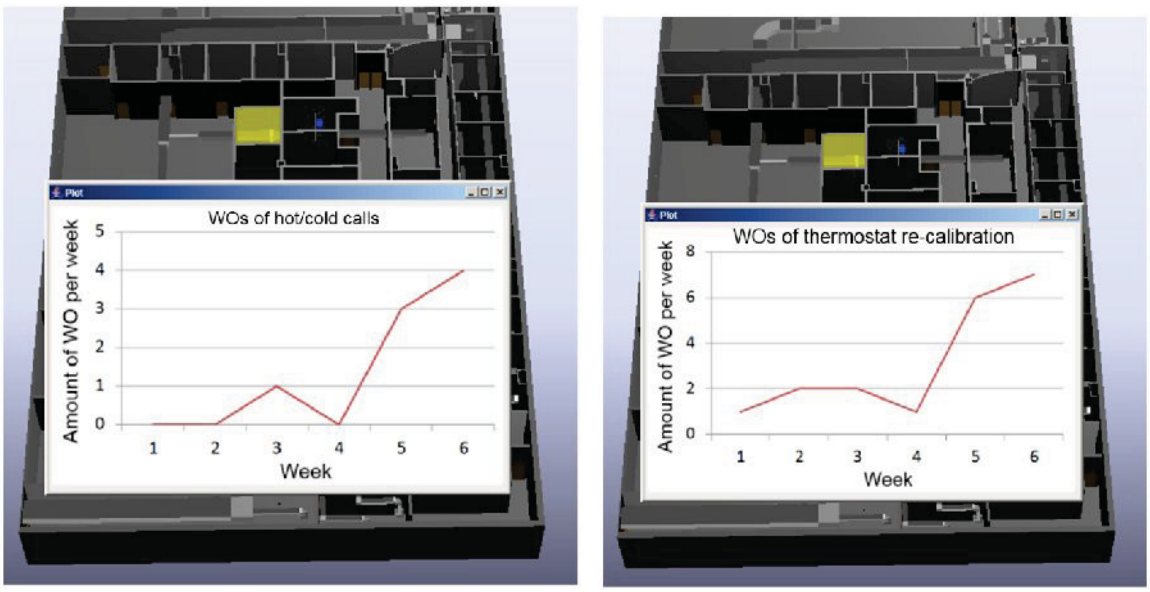
In Figure 2(a), the spaces that are related to the largest number of work orders are colored in red and the ones with fewest number of work orders are colored in blue. The other spaces with numbers of WOs in between are colored with a color based on the gradient given in the figure. This figure clearly shows the distribution of the work orders and enables the facility manager to identify the problematic spaces in an intuitive way. Similarly, Figure 2(b) visualizes the comparison of number of work orders that are associated with the components.

On the other hand, data trending visualizes the time-series to show the increasing or decreasing trend in the data. According to (Heer et al. 2009), time-series visualization approaches can be categorized into two groups: static charts and animation. Static charts include line charts, small multiples, and horizontal graphs. These charts are able to show the trend of single or multiple variables in one graph at one time. Due to the limited space in a single graph, static charts cannot clearly show the data if the number of variables is large (Heer et al. 2009). Animation is able to show multiple variables in a dynamic way so that only the data at one time point is visualized in the graph at a time. Therefore, animation is able to show trends in a larger number of variables. However, because the trend can only be perceived when people still remember the previous data, the animation approach is not proper for those data sets that occur over many time steps (Robertson et al. 2008). In this research, the objective of visualizing trends is to show the work order history in a single room or component for a relatively long period (several months), hence we used the static line charts to visualize the trend. Figure 3 shows an example of the visualized line chart that is implemented in the prototype.



(a) *(b)*

Fig. 2: Examples of visualizing the comparison of the amount of work orders that are associated with (a) spaces and (b) components



(a) Line chart of hot/cold calls WOs *(b) Line chart of thermostat re-calibration WOs*

Fig. 3: Examples of line chart visualization in the prototype to show the weekly number of (a) hot/cold calls and (b) thermostat re-calibration work orders

As discussed in the motivating case study, facility managers need to use the maintenance history to identify the abnormal conditions of the spaces or building components. For example, to analyze the cause of the *hot/cold calls* in a space, a facility manager can use the prototype to visualize the weekly number of repair work orders that are associated with the space. Figure 3(a) shows that the number of *hot/cold calls* increases over weeks 5 and 6. Figure 3(b) shows that there is also significant increase in thermostat re-calibration work orders during those same two weeks. These two trends suggest that the thermostat re-calibration work orders may be the cause of the *hot/cold calls*; therefore the facilities manager should inspect the thermostat to confirm the correlation and fix the problem.

By visualizing the work order information using color maps and line charts, the spatial and temporal analysis of the work orders are realized in a way that can assist the facilities manager in analyzing the spatio-temporal patterns of the work orders in the facilities and making associated decisions. In the following section, we will discuss the benefits and challenges we identified through the implementation of a prototype of our approach.

4. Lessons Learned

We formalized an approach to integrate the information collected in work orders with BIM and used visualization in a 3D model to provide information needed in Facilities Management. We developed a proof-of-concept prototype system that integrates a BIM model with work order information. This prototype utilizes the Open IFC Tool and Viewer (Tulke et al. 2010) to visualize the BIM and work order information in a 3D environment. The system enables a user to link work orders to facility model components and perform different types of queries. Hence, it enables analyses of the work orders based on different characteristics of the M&R work (e.g., type, cost, shop), properties of building components (e.g. type, location), and location and time of the work. To support the trending and comparison analyses of the work order information, we have been investigating the effectiveness of visualizing the information in a 3D spatial environment using color maps and line charts. We have identified several benefits that are achieved using the proposed approach:

- *Linking the work order information with spaces and components in BIM can enable spatio-temporal analysis of the maintenance history of the building components;*
- BIM provides a consistent naming convention for the spaces and components to improve the accuracy of work order information query; and
- Existing spaces and components in BIM can facilitate the information collection for work orders.

We have also learned the following challenges that are associated with the realization of the proposed approach:

- Some work orders are associated with several spaces or *components* that have different roles.

Currently, the proposed approach links all the relevant spaces and components to the work orders. However, some work orders are related with several spaces or components that have different roles. For example, if the occupants of Room A request a work order for the repair of the water leakage from the ceiling, Room A is considered as the relevant space of the work order. However, if the ceiling leakage is caused by the broken pipe in the Room B that is above Room A, the repair activity actually takes place in Room B. Although these two rooms are both directly related to this work order, they have very different roles because the repair task is only associated with Room B. Similarly, some work orders are also related to components that have different roles. For instance, in the example work order 1 from Table 1, the pipe and dry wall are both relevant components. However, the pipe is the cause of the problem and is replaced, while the dry wall is opened up and repaired because the plumbers needed to access the pipe. Therefore, it is challenging to use the proposed approach to handle these scenarios.

- The levels of detail of BIM limit the possible *linkage* with work order information.

Work orders are associated with many different types of components in the building. For example, a work order maybe related to the replacement of furniture, such as tables and chairs. Another work order maybe related to inspection of the connection of two HVAC ducts. Therefore, to link these work orders with BIM, these components should already exist in the model. However, the model might only have HVAC components, but not the furniture or vice versa. Currently, different levels of detail are used in BIM and users need to define these levels based on their requirements. A certain level of detail of BIM should be defined for enabling links with work orders and it is challenging to ensure that the all relevant components in the work order can be found in BIM.

- There is inadequate information in the work orders.

We have conducted two test cases using the work order records from a university building and a hospital building. The result showed that many work orders do not contain information of the relevant space or components. Therefore, they cannot be linked with BIM and the history information cannot be used for analysis and decision support. It is challenging to change the current practice of documenting work orders to include all the needed information. However, there are current research studies that can address this problem such using field data capture technologies(Kiziltas et al. 2008) and customizing the work order templates according to information needs of different types of maintenance and repair work (Akcamete et al. 2011).

5. Conclusions

The approach described in this paper addresses the need for storing and visualizing maintenance and repair work order information in a 3D model so as to perform spatial and temporal analysis of WO records. We developed a proof-of-concept prototype that can automatically link the WO information to BIM and spatially visualize this information by enabling spatio-temporal queries. Temporal analysis is used to show the trend of work orders and spatial visualization allows data comparison for identifying abnormalities. To support the trending and comparison analysis of the work order information, we have visualized the information in a 3D spatial environment using color maps and line charts. The development of the prototype has enabled us to identify some potential benefits and challenges associated with the implementation of our approach. In our preliminary user study, we observed the potential of this integration and visualization in enabling the analysis of maintenance history and supporting of informed facility management decisions. We implemented automated linking of WOs with spaces and facility components and hence realized the challenge of storing the information about the components that are not represented in BIM. Correspondingly, we have realized the need for different levels of detail of the model for supporting different visualization needs of facility managers. Moreover, we identified a need for linking multiple types of information (e.g., cause of a WO, or the location of a WO) to the same space or component and effectively visualizing these differences. In addition, the approach highly depends on the information items that are captured in the WOs, since without information about the relevant components or spaces it will not be possible to realize the integration. The possible benefits of such a system is promising, however further research is necessary to address the identified challenges and for achieving a fully competent system.

6. Acknowledgement

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PROCEDURES TO INCORPORATE INTERACTIVITY IN VIRTUAL PROTOTYPES USING A GAME ENGINE ENVIRONMENT

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ABSTRACT: *Participatory design approaches that require end user involvement in the decision-making phase of design can benefit greatly from a virtual facility prototyping system that is interactive. This paper explores various methods through which we can incorporate interactivity in a virtual facility prototype using a game engine called Unity. We discuss procedures to develop a facility model and transfer it into the Unity game engine along with strategies to make these processes more efficient and repeatable. Using Unity affords some unique features that enable rapid content generation and relatively easy transfer of design information from external 3D modeling tools such as Autodesk Revit and Google SketchUp. Once the facility model is in the Unity game engine, we can incorporate basic physics, collision detection, rigid bodies, event engines and GUIs in the facility model and develop the required level of interactivity for our prototype. Some of the interactivity features we investigate include the development of navigation modes, menus, interactive objects with triggers as well as scripts that keep track of the tasks or scenarios that could be performed in the facility. Navigation approaches discussed in the paper include methods to employ either a first person controller or a third person controller using an avatar model that depicts the end user. We then demonstrate a strategy to design menus and develop scripts that track tasks performed in the virtual facility based on the type of interactivity desired from the prototype. We also illustrate the use of triggers to develop objects that are interactive - a door that swings open in proximity of the users navigating the virtual prototype of the facility. The paper is concluded with some lessons learned and future steps on making virtual facility prototypes more interactive for end users during design review.*

KEYWORDS: *virtual prototypes, game engine, interactivity, Unity game engine, healthcare design*

1. Introduction

Virtual Prototypes are increasingly being used during design reviews of specialized buildings such as healthcare facilities. However, most of these virtual prototyping approaches do not allow the reviewers and end users to interact directly, in real time with elements and objects within the virtual model. This research is focused on changing the fundamental approach toward reviewing the prototypes by developing a more interactive virtual experience for the user that allows them to explicitly perform typical tasks just as they would in a physical setting. Enabling the end users to interact and navigate their facility model within a virtual environment through the eyes and actions of an avatar could help improve the quality and quantity of their design review comments. The approach will also enable design professionals to enter their design in the role of end users through pre-scripted scenarios of typical activities. Moreover, it could help demonstrate incompatibilities between equipment (e.g., wheelchairs and walkers) and the architectural geometry, giving the design professional opportunities to modify the design of the building prior to construction when it becomes very cost prohibitive. Ideally, the reviewers would be able to navigate a model that is directly translated from standard three dimensional (3D) design authoring tools to game engine systems, which include interactive prototyping capabilities. To be able to make effective use of these interactive prototypes, it is important to develop workflows and standard procedures that allow for rapid development of interactive virtual prototypes.

This paper is an extension on developing an experience-based virtual prototyping application using a 3D game engine (Kumar et al. 2011), that explores various methods and procedures to incorporate interactivity in virtual prototypes and explore efficient workflows of transferring design information to a prototyping environment for real-time navigation and increased user interactivity with the virtual prototype of a facility.

1.1 Problem Statement

While virtual prototypes are useful for design visualization, allowing the review participants to walk-through the design of a facility to examine the space, textures and lighting, they are typically implemented in a static manner. Most virtual prototypes do not allow the user to interact directly with the elements and objects within the virtual model. Moreover, visualization in virtual prototypes is a challenge due to the lack of human characters (or avatars) and animations that depict how the facility is used or the tasks performed within the facility. At present, the prototyping process typically lacks a systematic structure or method to allow for task-based scenarios to take place for the review participant. Although a Building Information Model (BIM) of the facility contains geometric and attribute data that is transferred in the virtual prototype, there is no information on the behavior of the components within the facility. For instance, doors modeled in a facility do not swing open in a virtual prototype, despite containing intelligent attribute information such as location of its hinges. As a result, while reviewing, participants either walk through doors or they are not shown in the prototype. This is because animation is still cumbersome to incorporate while developing the prototypes, which can lead to an unrealistic representation of the facilities. Due to these challenges, most current virtual prototypes do not enable people to truly experience the design. The use of game engines can enable participants to interactively perform certain task-based scenarios within the virtual prototype. However, there is a lack of workflows and procedures to quickly convert 3D models of facilities into interactive virtual prototypes for real-time visualization in these game engine environments. This paper seeks to investigate methods, tools and applications that can be employed to develop interactive virtual prototypes more efficiently.

2. Background

Traditional forms of representation techniques such as photos, drawings, and animations are limited in conveying knowledge about how architectural structures are made, how they work, how they influence people's perception of space and so forth. It is also widely accepted that real-time visualization (i.e. games engines) can enhance the design in various stages as well as better present concepts because a virtual environment reduces the mental effort required to comprehend a 3D world by assigning relevant content at specific design stages and provides possibilities for user directed exploration (Calderon et al. 2006).

Virtual prototypes are being increasingly used during design review since they can be especially useful for the design of specialized building types that involve a diverse range of stakeholders during the design process. Virtual prototyping provides opportunities for a team of project stakeholders to truly experience design alternatives and concepts in the early stages of the design process. While helping in design review, virtual prototyping also allows multiple participants to navigate through the model space and evaluate the design based on various criteria through numerous vantage points within the model. Prior studies have shown the value of using virtual prototypes during design review of facilities such as courtrooms (Majumdar et al. 2006; Maldovan & J. Messner 2006), operating rooms, patient rooms (Dunston et al. 2010), as well as indicated the benefits of using them over physical mock-ups (Leicht & J. I. Messner 2009). Moreover, these studies have highlighted the opportunity to enhance end user engagement in instances where team members leverage and communicate their tacit knowledge, enabling collaborative interdisciplinary participation over the early stages of the design development process

2.1 Interactivity

Interactivity is defined as the extent to which a user can participate in modifying form and content of a mediated environment in real time (Steuer 1995). The role of interactivity is to generate greater involvement or engagement with content (Sundar 2007). Most, if not all, modern-day interfaces are interactive, empowering the user to take action in highly innovative and individualized ways. Fundamentally, interactivity converts a system into a communication medium, by eliciting user interaction with the interface. Interactivity influences the user by increasing/decreasing perceptual bandwidth, offering customization options and by building contingency in user-system exchanges. They all contribute in different ways to user engagement in terms of cognition, attitude, and behavior.

Interactive features are important for users of the virtual environment as it helps them relate what they are seeing in the virtual environment to the real world (Wang 2002). For instance, end users can also be placed in a simulation as avatars and then simulate movement-based scenarios and virtually walk through a design. Unlike pre-scripted walkthrough or flythrough videos, movement is not forcefully prescribed or scripted. This allows end users to interact with the virtual facility and perform collaborative exploration of the designed environment.

2.2 Interactive Virtual Prototypes Using Game Engines

Game engines are the core software component that provide the underlying technology, simplify development and incorporate all the elements vital in a game like physics, collision detection, graphical user interface (GUI), artificial intelligence, network functionality, sound and event engine (Eberly 2007; Fritsch & Kada 2004). Most game engines have a built-in physics engine that supports basic physics, collision detection, rigid body and vehicle physics. However, at present there is only an insignificant relationship between game engines and standard architectural or design visualization tools as they seldom offer real-time rendering and simulations that game engines do.

Gaming consists of “interaction among players placed in a prescribed setting and constrained by a set of rules and procedures” (Hsu 1989). Contemporary developments in gaming, particularly interactive stories, digital authoring tools, and collaborative worlds, suggest powerful new opportunities for educational media. While gaming environments and simulations are becoming more and more widespread in education, very little is known about how they work (Squire 2006). Similarly, in the design context, unlike reviewing virtual prototypes of facilities in virtual environments, gaming environments can offer extensive possibilities to engage end users through interactive simulations of task scenarios within the virtual prototype. However, in order to employ gaming environments in the design review of virtual prototypes, it is important to understand how games and simulations can be developed. Furthermore, game engines allow multiple simultaneous users to explore the designed environment. According to Shiratuddin (2004), with the advances in networking system for online games, one of the strengths of the game engine is its capability for multi-participant networking. The inherent multi-user nature of the game technology lets clients connect to its server using the game's client software over the Internet.

2.3 Unity Game Engine

The Unity game engine has a robust feature set that allows for customization, is affordable, and has a relatively easy interface with drag and drop ability making it easy to learn and use. The Unity game engine was chosen as a feasible option to develop interactive virtual prototypes due to its low cost and relative ease of use and as it can be used in both Mac and PC operating systems. The game engine uses Just-In Time (JIT) compilation in the readily available C++ mono library. For the purposes of rendering, it uses the Nvidia PhysX physics engine, OpenGL and DirectX for 3D rendering and OpenAL for audio. Various workflows are being explored to conveniently transfer Autodesk Revit, Google SketchUp and Autodesk 3DS Max building model content to the Unity Game engine.

Within each Unity project folder, there is a default Assets folder that performs the function of an element library for the facility. The *scene* file is also located in this Assets folder and includes the main levels as well as different zones and spaces of a facility prototype. Moreover, all elements that are ever used in the scene including game objects, prefabs (objects with attached behavior scripts), textures and other components along with their behavior scripts are stored in the Assets folder. These elements, referred to as assets in the Unity game engine can be reused from one project to another. Within the Unity game engine interface, the elements stored in the assets folder are displayed in the *Projects* tab. A facility prototype developed in Unity will consist of a single Unity Project folder that contains all the project's elements, such as models, scripts, levels, menus, etc.

3. Developing Workflows for Virtual Prototypes

The objective of this research is to streamline the development process so that the amount of time and effort required in creating interactive virtual prototypes of facilities could be reduced. The development of design information workflows from 3D modeling software to a game engine environment is required to enable efficient transfer of design information. Various workflows have been developed and tested to utilize 3D content from different BIM authoring tools to a game engine environment. These design information workflows have also helped identify challenges in the workflows and the manual time consuming tasks related to texturing, positioning, and lighting that are required in this conversion (Kumar et al. 2011). Since the Unity game engine supports model imports from almost all 3D applications, facility models were developed in both Autodesk Revit Architecture and Google Sketchup. Then these models were exported as an FBX file format and opened in Autodesk 3D Studio Max Design application. This is a crucial process for importing facility models in Unity as 3D studio max is a great program to optimize the model geometry and meshes to reduce polygon size and excessive detail which can quickly add up in a Unity scene creating a slow and unusable file. The file size is reduced by approximately 40-60 percent using 3DS max and the FBX file format exported has all the relevant texture and lighting information to be adequately used in Unity. Facility models exported as an FBX file from 3DS max can be imported into Unity as a new asset.

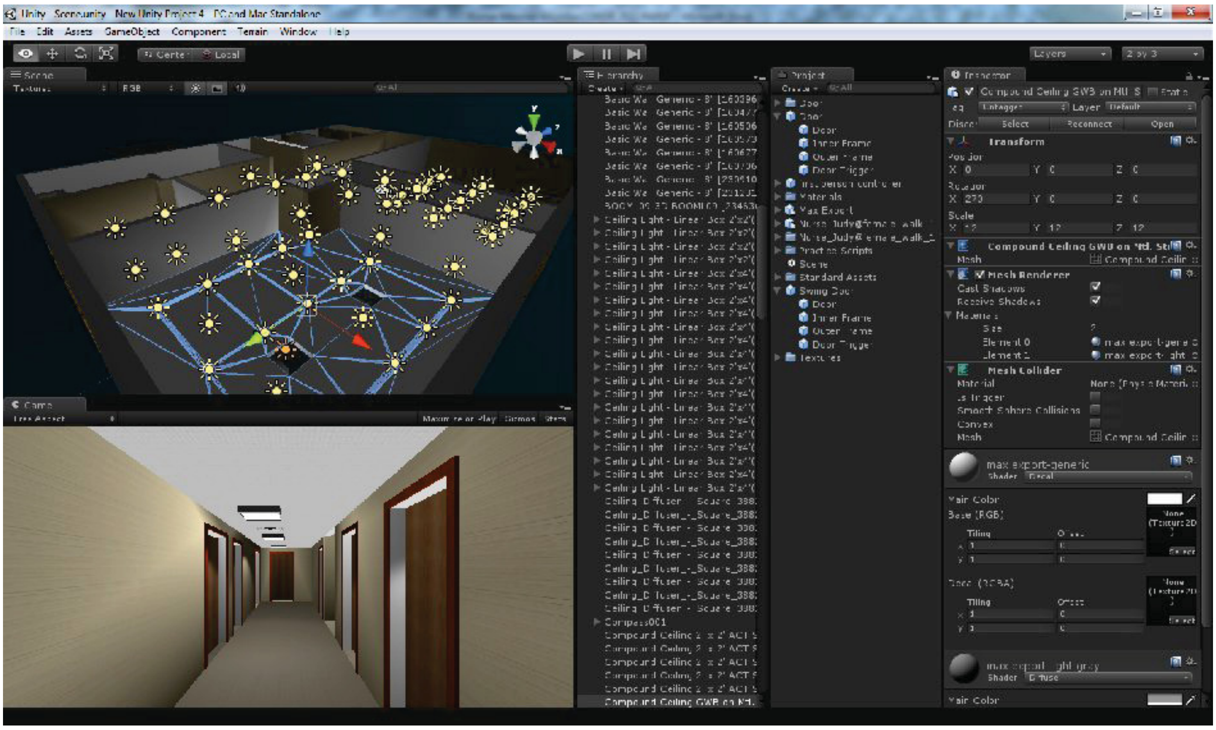

Fig. 1: Unity game engine interface showing a facility model

Unity is asset-centric rather than code-centric, placing the focus on the assets in much the same way as a 3D modeling application. Unity's design places each scene's assets at the center of the development process. This makes for a very visual approach to game development, with most of the work involving dragging and dropping. Scripts define how assets and *GameObjects* in a Unity Scene interact with each other and this interactivity is at the core of all Unity projects.

3.1 Reusable Interactive Model Content

The use of *Prefabs* enables creation and development of interactive objects that combine the 3D geometry as well as physics and related behavior for objects to appear as they would in the real world. A player character Prefab, for example, could be defined as a single Asset, containing the model and its associated animations. It could also contain script components, audio clips and any other components it needs to function, so that one could simply drag it into a Scene and instantly have a fully operational avatar.

The ability to package these prefabs within the Unity game engine allows the reuse of these objects across various projects. Over time, a repository of these assets can be created that can facilitate in saving time and resources. The use of the Unity game engine for real-time scenario-based architectural visualization was implemented in a university course on virtual facility prototyping. Students in this graduate class explored various methods and ways to incorporate interactivity. First, the students familiarized themselves with the Unity interface, followed some tutorials and then they investigated information workflows to transfer their facility models from architectural modeling applications like Autodesk Revit and Google SketchUp into Unity.

4. Procedures to Incorporate Interactivity

Within a virtual prototype, there are many types of interactive examples that occur. One of the first modes of interactivity could be a user customized menu, where users can choose what facility they want to explore or through which role they want to walk through the facility. Once in the facility chosen, the user interacts with the virtual prototype through real-time navigation of the facility. This could be either through a first person controller, also known as the First person shooter (FPS) in video game terminology or one could have 3D character controllers of various user roles (also known as avatars) to navigate the facility. Another important aspect of interactivity is the graphical user interface and the various functions that are available to the user while navigating the facility. These could include a minimap that helps in navigation and wayfinding within a facility and multiple camera views with the ability for the user to control what they wish to review within the prototype. Users can also interact with a menu to keep track of the various scenarios of tasks they can simulate to perform within a facility.

One of the first steps after importing the facility model geometry inside the Unity Game Engine is to attach properties and behaviors to the elements of the model. Usually most of the elements such as walls, floor, furniture and other immoveable objects in the facility model should behave as solid object and a user navigating through the virtual facility prototype should not be able to pass through them. This is achieved in the Unity game engine by attaching a *Collider* component to such objects. The *Collider* component can be applied either as a mesh or a primitive object over the 3D object model that is rendered in the scene. Once appropriate colliders are attached to various elements within the model, a character controller can be added for the user to control their navigation within the virtual prototype.

4.1 Navigation

Architectural walkthroughs are usually static flythrough videos that give a virtual tour of a facility by displaying to the user pre-mediated views of the design. Real-time rendering applications enhance user interactivity by supporting several navigation modes, such as *Walk, Fly, Examine,* etc. and almost all applications support the *walk* mode for architectural walkthroughs and game design. In most applications which use interactive 3D graphics as a platform, this navigation can be portrayed either from a first person point of view or a particular character's point of view. Using the Unity game engine, we explored feasible ways of incorporating both modes of navigation along with providing greater camera control for the user.

4.1.1 First Person Controllers

In a first person controller, the camera is the player's point of view, so there is no need to worry about making it follow another object around the scene. The player controls the camera object directly. First person cameras are therefore relatively easy to implement. Within the standard assets in the Unity Game Engine, there is a First person controller that can be dragged into the scene or hierarchy window. The first person character controller comprises of a capsule geometry, camera attached for eyes and a script that enables motion on user input. Some of the variables that can be controlled and modified by the user include speed, rotation, camera view rotation, and jump. While navigating, the character controller will not be able to go through objects that have the *Collider* component attached due to collision detection of the underlying Unity physics engine.

4.1.2 Third Person Controllers

Since developing user character avatars in 3D modeling applications and animating them can be very time-consuming, our research team found a website of a company called Mixamo (http://www.mixamo.com/) that allows the download of custom characters with required character animations that include walk, sit, idle and many more character motions that can be used during the review of a virtual facility prototype. The website also allows custom characters created and developed in other 3D modeling applications to be uploaded on the website to attach animations. After the character or avatar is imported into Unity as an asset, character controllers and other scripts can be attached to enable third person navigation. Usually a camera is attached a set distance behind the character controller within the hierarchy in a parent-child relationship. This enables the user to view the facility prototype through the camera that constantly follows the third person controller.

Fig. 2: Character controller depicting a nurse downloaded from www.mixamo.com

4.2 Graphical User Interface (GUI) Design

A Graphical User Interface (*GUI*) represents the information and actions available to a user through graphical icons and visual indicators. In Unity, the GUI system is called UnityGUI. UnityGUI allows the creation of a huge variety of GUIs complete with functionality very quickly and easily. Rather than creating a GUI object, manually positioning it, and then writing a script that handles its functionality, these functions can be done all at once in a small amount of code.

4.2.1 Menu Design

A start menu can be launched when the virtual prototyping application developed in Unity is opened. Similar to video game development, start menus can enable the user to change options and enter the virtual prototype of the facility (Kumar et al. 2011). The start menu for the virtual prototype of the facility can generally be saved as a separate scene with buttons or textures that allow the user to choose which spaces they want to explore or what role they want to choose. Based on their choices, different levels or *Scenes* are loaded in the Unity application for the user to explore.

Fig. 3: Start Menu with interactive buttons to load levels and change options

4.3 Interactive Objects

For real-time architectural visualizations, there is often a need to have moveable objects and navigation through the virtual prototype. The Unity game engine is setup to show visual assets, however, these also have to be connected to each other to provide the interactivity expected in the virtual prototype. These connections are difficult to show visually. These connections are known as dependencies, and it's what you get when one object requires a second object to function. That second object may, in turn, require yet more objects to work. The result is that your assets are tied to each other with myriad virtual bits of string scripts tying them all together to make a game.

While navigating through the facility, one often needs to pass through doors that open or move a trolley or wheelchair from one space to another. This interactivity in the virtual prototype can be achieved by adding animation to doors that can swing or slide open and physics to objects that move when force is applied to them by another object such as the character controller in the game. Alternatively, this movement or animation can also take place with mouse clicks or triggers. Triggers could also take form of objects that enable an action to take place on either proximity or clicks or certain keyboard commands. Triggers are invisible *Components* which, as their name implies, trigger an event. In Unity, any Collider can become a Trigger by selecting its *Is Trigger* property and setting it as true in the Inspector window.

A user can usually walk past the door in a facility model, since the door does not have a *Collider* component attached to it. However, in real-time navigation of a virtual facility prototype, the ability to make the door swing open can increase the level of realism and experience of the user reviewing the facility. This can be achieved by adding an animation on the door object in the Unity game engine that enables it to swing open. Additionally, to ensure that the door only opens when a user approaches it, triggers can be used, either for detecting proximity of the character controller or through some user input. An invisible collider trigger object of the required dimensions can be superimposed on the door object such that when the user collides with the trigger object, it enables the door animation to play and the user can walk between spaces once the door has swung open as shown in figure 4. On repeated trials to make the door swing open, it was realized that the door and door frame were combined as a single object and it was not possible to split them within Unity. Thereafter, it was realized that to simplify the incorporation of swinging doors in the virtual facility prototype, it was necessary to split the door frame and door panel in the authoring application such as Autodesk Revit Architecture, where the door family is edited to split and create two distinct door objects- the door and the door frame.

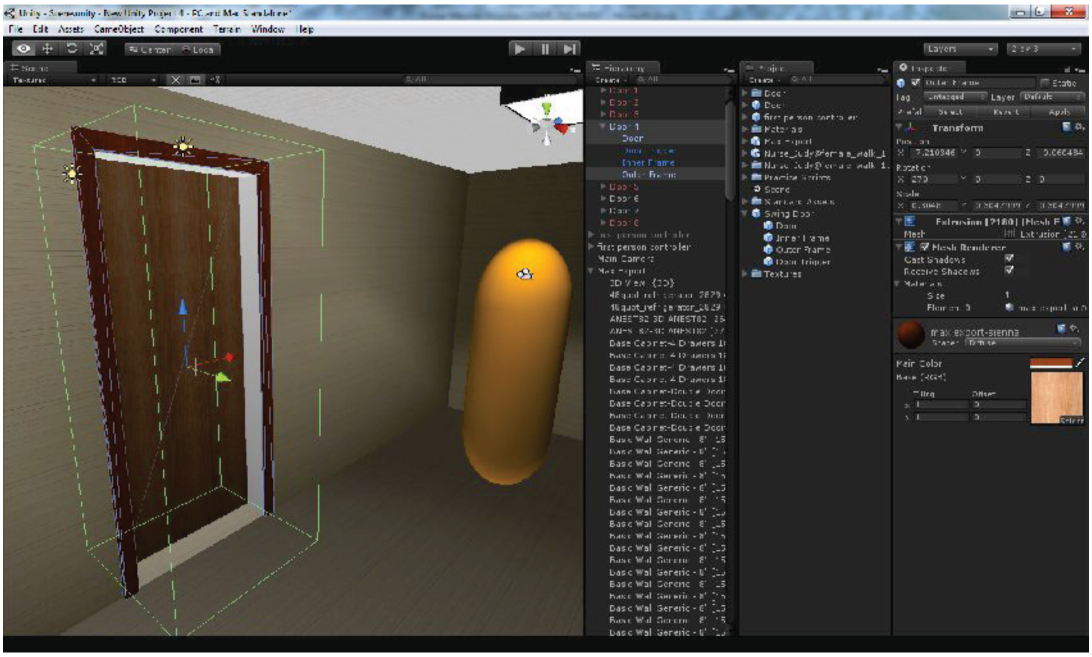

Fig. 4: Door Prefab showing the invisible door trigger collider and the separate door and door frame objects in the hierarchy.

4.3.1 Scripting

To manage the scenario tracking process, two scripts with unique roles were developed- *the trigger monitoring script* and *the scenario monitoring script.* The trigger script is responsible for checking to see if the user is interacting with the correct object at a given step of a specific scenario. The scenario monitoring script observes which step of a given scenario the user is on and ensures that proper instructions are displayed on the user interface. Each game object is assigned a unique identity, and the trigger monitoring script is applied to each object via a simple drag and drop interface in Unity 3D. Having to apply the trigger script to each individual game object will increase the total amount of code used in a given simulation, but is a simplistic fix to eliminate the use of more advanced coding techniques. Many of the programming strategies that follow could be significantly simplified with an intermediate to advanced level of knowledge of JavaScript and C#.

The Trigger Monitoring Script is governed by three chief variables defined within its code and a series of *if* statements that determine what step of a scenario task the user is on. When certain conditions have been met, the script allows the user to progress to the next step in the task. All three of these variables are also passed on to the Scenario Monitoring Script which is responsible for displaying the current task information on the user interface.

Table 1: Scenario Tracking script with its variables and functions

Variable	Function
Scenario Count	Each value corresponds to the selection of a different scenario
Step Count	Corresponds to the current step of a scenario task that the user is on
Object Value	Identifies the object and allows the TMS to verify that it should be used at a given step.

With reference to the three variables from table 1, a set of three *if* statements must be modeled in code for every possible step of a scenario task. If any of the three *if* statements are false, then the step is incomplete and the user cannot progress to the next task. In summary, each of these if statements analyze the following conditions:

1. Has the user completed all of the prerequisite steps prior to the current step?
2. For a given step, is the user interacting with the correct object?
3. Has the user completed the current task step?

If each of these three conditions are met with the code equivalent of a 'yes,' then the value of the *Step Count* variable is increased by one, signifying that the user is able to progress to the next step in the scenario task.

Fig. 5: Tasks performed by user in virtual facility prototype tracked by the Scenario Tracking script displayed on the graphical user interface

5. Conclusions

This paper discusses the procedures to incorporate interactivity in virtual prototypes of facilities to enhance end user involvement and engagement in the design process. We used the Unity game engine to transfer models of facilities created in external 3D modeling tools and added physics, collision detection and other modes of interactivity in the virtual facility prototype. Apart from that we explored various navigation modes that included simple first person controls all the way to the use of avatars for third person control. Other scripts and use of triggers enabled objects to become dynamic and interactive, so that we had doors that could swing open and objects that could be moved within the virtual prototype of the facility. We also implemented the use of Unity game engine for the development of interactive virtual prototypes and real-time architectural visualization in a graduate research class on virtual prototyping. Working with students on Unity helped us explore many more features that it offers along with creation of more design content for testing. Apart from the modes of interactivity discussed in this paper, we have also developed other menu features that include mini maps, scenario and tasks trackers, different camera views, ability to turn lights on and off and toggle visibility of various components in the facility prototype. We are continuously refining many of our procedures to incorporate interactivity in these virtual prototypes that has also led to some guidelines for future development.

5.1 Lessons Learned

The Unity game engine proved to be a very useful tool for incorporating interactivity in the virtual facility prototype as well as for real-time architectural visualization with different navigation modes. The workflows for transferring design information from various 3D modeling tools has been a highly iterative process that included a lot experimentation and going back and forth between various software tools before determining the most effective process. Although we mostly used Autodesk Revit and Google SketchUp as the initial tools where the facility models were created, it was determined that Autodesk 3DS max is an important intermediate tool to transfer the facility model before bringing it into the Unity game engine. 3DS max helps streamline the model content and refine the textures on the elements of the model. Within Unity, like many similar game engines, adding physics and interactivity is relatively straight forward.

Changes made in the original model in external 3D modeling tools can be updated with the same file name and all the changes are incorporated in the model in Unity. Using prefabs in Unity enabled us to package behavior scripts with 3D geometry which allowed us to use the same content such as first person controllers and swinging doors without manually repeating the effort. This streamlined the process to a great extent and we foresee many possibilities of using Unity on multiple projects across many facility prototypes. We referred to many online tutorials and the Unity website to grasp the use of various functionalities offered. Although there seem to be endless opportunities for adding various elements and features of interactivity, there can be a steep learning curve for beginners, especially when there is a need to add custom behavior scripts. Although a lot of content is packaged in Unity and the Inspector window enables easy manipulation of object variables, to truly customize the level of interactivity and add advanced functionality, appropriate programming knowledge and background is highly recommended. We realize that with more development and refinement, interactive virtual prototypes of facilities can have tremendous potential in involving end users in the decision-making process during design which is discussed further in future steps.

5.2 Future Steps

Interactivity not only enables the end users of the facility to interact with the virtual prototype during design review, but also gives the AEC professionals an opportunity to review the prototype through the roles and point of view of the end users. Interactive virtual prototypes can prove to be effective design communication tools between the professionals and end users by extracting domain specific tacit knowledge from both parties to create better understanding of the facility which further leads to better design. Hence, there is a need to further refine these processes to make virtual prototypes more interactive by finding more effective and less time consuming ways to implement them in project teams. There is a further need to study and document the advantages of using interactive virtual prototypes by various stakeholders in the design process and determining additional functionality and interactivity that may be required to make the virtual facility prototypes more useful.

6. Acknowledgements

The Authors would like to acknowledge the students of the AE 597F Virtual Facility Prototyping class for using Unity for their projects and helping streamline the various processes to incorporate interactivity in their models. We would also like to thank Chuck Hixon from Bergmann Associates for helping us with queries on using the Unity Game Engine for real-time architectural visualization.

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3D VISUALIZATION OF MODULAR BUILDING ASSEMBLY: FROM A FACTORY TO CONSTRUCTION SITE

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ABSTRACT: *Buildings are constructed using traditional on-site construction methods or industrialized (i.e. manufactured in components or modules). Modular building is the highest degree of industrialization of the building construction process. In this context, the manufacturing of buildings in a factory and their shipment in modules to the site, demands a new approach to scheduling and resource use. Because of their large geometric volumes, handling the modules especially on construction sites can be extremely challenging. As a result, 3D visualization tools are critical for precise planning since they allow one to resolve beforehand any spatial constraint such as collisions with existing obstructions and lifting paths feasibility. This paper addresses the two most important aspects of modular construction: 1) shop manufacturing and 2) on-site assembly. In this respect this contribution describes a methodology which integrates simulation models and post-simulation 3D-Visualization. The integration of these tools provides a framework allowing to gain a detailed insight into the dynamics of the manufacturing and assembly processes and also to gauge the risks related to the work-space and interference of modules with the surrounding obstacles. The proposed methodology is validated by a case study that involves the construction of five (5) student dormitories for Muhlenberg College, Pennsylvania, USA. The five (5) buildings are each 3-storeies consist of 18-modules, totaling 92-modules for all five buildings. The 92-modules were manufactured at Kullman (a modular manufacturer in New Jersey, USA).*

KEYWORDS: *3D visualization, modular, simulation, optimization, construction site, crane operation.*

1. Introduction

The primary advantages of industrialization of the construction process are an environmentally-friendly construction process, short completion time, and cost-competitive technology. Modular construction has extended its applications to schools, hospitals and hotels that allow for the easy and efficient modularization of a variety of shapes (Cardenas and Domenech 2005, Dolan 2006). Successful applications related to modular technology also include the construction of specialty health care units, pharmacy centers, single-patient check-up rooms, and operating theatres (Veale and Postawa 2007). Although "modular" usually refers to single unit, low-rise multi-family residences, high-rise facilities can be a perfect fit for modular construction (Cartz and Crosby 2007). Designing the production line in the manufacturing process is complex and combines line-flow product movement with a complex network of activities involving physical and space constraints. However, despite such constraints, modular construction can be efficient since it heavily relies on shop manufacturing which offers an environment where high quality standards, e.g. increased productivity, optimal control of waste be it of material or manpower, a better process flow, may be maintained at all time.

In this context, lean manufacturing concepts, which were originally developed for the automotive and air-space industries, have been widely used for modular construction. As a result, the production process and material flow in a building's manufacturing plant can be continuously improved by streamlining resource utilization. In practice changes, which are thought to be beneficial, to the manufacturing chain are first tested using a simulated model of the chain in order to quantify their effects on quality and productivity without disturbing production (Senghore 2001). In the context of modular construction several case studies used simulations to quantify the cost and/or improve the efficiency of the manufacturing chain were documented in the literature. The effect of manufactured housing components' assembly on productivity has been studied based on the material handling cost of the facility layout (Sabharwal 2004). Also, a supply chain management system has been developed (Jeong 2003, Arbulu and Tomelein 2002) with a view to optimizing process time from order to installation. A decision support system for manufactured housing production process planning and facility layout has been introduced to reduce the cycle time of the production process and enhance the quality of material for productivity improvement (Hammad 2003, Haitao et al. 2008, Wang et al. 2009, Haitao et al. 2009). It identified inefficient production processes and layout limitations to the production capacity and helped to develop a streamlined manufactured building process, optimize models to streamline activities, predict relevant parameters, and advance layout designs.

When modules are manufactured, they are delivered to construction sites for assembly. In respect to construction site assembly operations, cranes are critical tools by which to place components and handle materials. Some construction sites have limited space availability so the location and swing space reserved for crane maneuverability are the main factors which lift engineers must consider. With the increasing complexity of crane layout, industry has developed tools to assist practitioners in the selection and optimum utilization of cranes (Manrique et al. 2007). Furthermore, the complexity of the lifts varies based on the type of construction site, some lifts could be simple and straight forward, while others consume a fair amount of time in preparation and detailed lift analysis. A genetic algorithm (Tam et al. 2001, Jacek Olearczyk et al. 2008) has been used to optimize tower crane operation; whereas, a path planner for crane lifts has been developed (Matsuo et al. 1991, Sivakumar et al. 2003, Shih Chung Kang and Eduardo Miranda 2006).

Implementing changes on-site without prior validation and verification can be risky, costly, and time-consuming; alternatively, computer simulation is an efficient and cost-effective tool to experiment with potential alternatives. However, current simulation tools used in construction describe an abstraction of the real-world which a number of users have difficulty understanding.3D visualization could be an alternative tool in combination with simulation to help users easily understand construction processes. Previous research (Juan et al. 2007; Mohamed et al. 2005; Abourizk and Mather 2000; Beliveau et al. 1993; Koo Bonsang and Martin Fischer 2000; Staub-French el al. 2008, Jacek Olearczyk et al. 2009) has proved that 3D visualization is an effective tool for various purposes such as space conflict, site layout, and construction sequences. Al-Hussein et al. (2005) and Moselhi et al. (2004) have introduced an algorithm by which to choose the optimal crane with respect to lift capacity while utilizing 3D animation for visualization techniques.

This paper focuses on using 3D visualization to improve modular building production assembly line and develop crane operation and position on-site to optimize sequential lifting patterns. A case study was implemented that ninety-two (92) modules were manufactured at Kullman shop, New Jersey, USA, and shipped to erect them on a construction site, Muhlenberg College in Pennsylvania, USA.

2. Methodology

The proposed methodology (as illustrated in Figure 1) is divided into two categories: 1) the process of a factory to improve an existed production process and 2) the process of on-site to optimize crane operation. The main process of the factory consists of three distinct phases which are the Value Stream Mapping (VSM) as a lean tool, simulation, and visualization. Based on the current scheduling, transfer time, activities' process times at each station, and cycle time of a manufacturing production line, current VSM is built to analyze the current production line and determine which problems and wastes can be eliminated. After identifying the problems, the focus is on considering pull system, instead of push system, and takt time when a proposed production line is developed with eliminating wastes. One of the main concepts in lean is that the factory must produce products according to customer demand which indicates takt time. The pull system means that an upstream task should produce a product until a downstream task asks for it. The time data used in simulation is converted to probability distribution functions. Two simulation models in Simphony software (Hajjar and AbouRizk 1999) are built with transfer time between stations, activities' process times at each station, and existing and proposed schedules. The cycle time statistic and productivity from the current and proposed state simulation models are compared to validate the proposed production process. The simulation output includes the modular cycle time statistic and the ASCII file which is composed of start and finish times of activities and travel times between stations. It is a unique file that can import the simulation result into 3D Studio Max as a visualization tool. To generate the ASCII text file from the proposed simulation model is a keynote to share information between simulation and visualization. Modular components' specification, the proposed production process fitted in the simulation model, transfer time, 3D components required in the production process, and the ASCII file are used to develop the 3D visualization model in 3DS.The process time of each activity from the ASCII file is assigned to 3D objects in Maxscript without repetitive work. The Maxscript is a built-in-language in 3DS and can build a user interface to prevent repetitive work to rebuild animation when the process times in ASCII file are changed from the simulation model. The 3D visualization output involves a virtual reality model with a 3D scheduling chart. Based on the pull system and takt time in lean, the virtual reality model validates and verifies the proposed production process such as workers' co-operation and collision which could not be identified in the simulation model. The bar charts are animated over the activities' process times while 3D components related to the activities are animated simultaneously. It helps users to identify the proposed scheduling errors and the state of the activity process at specific time.

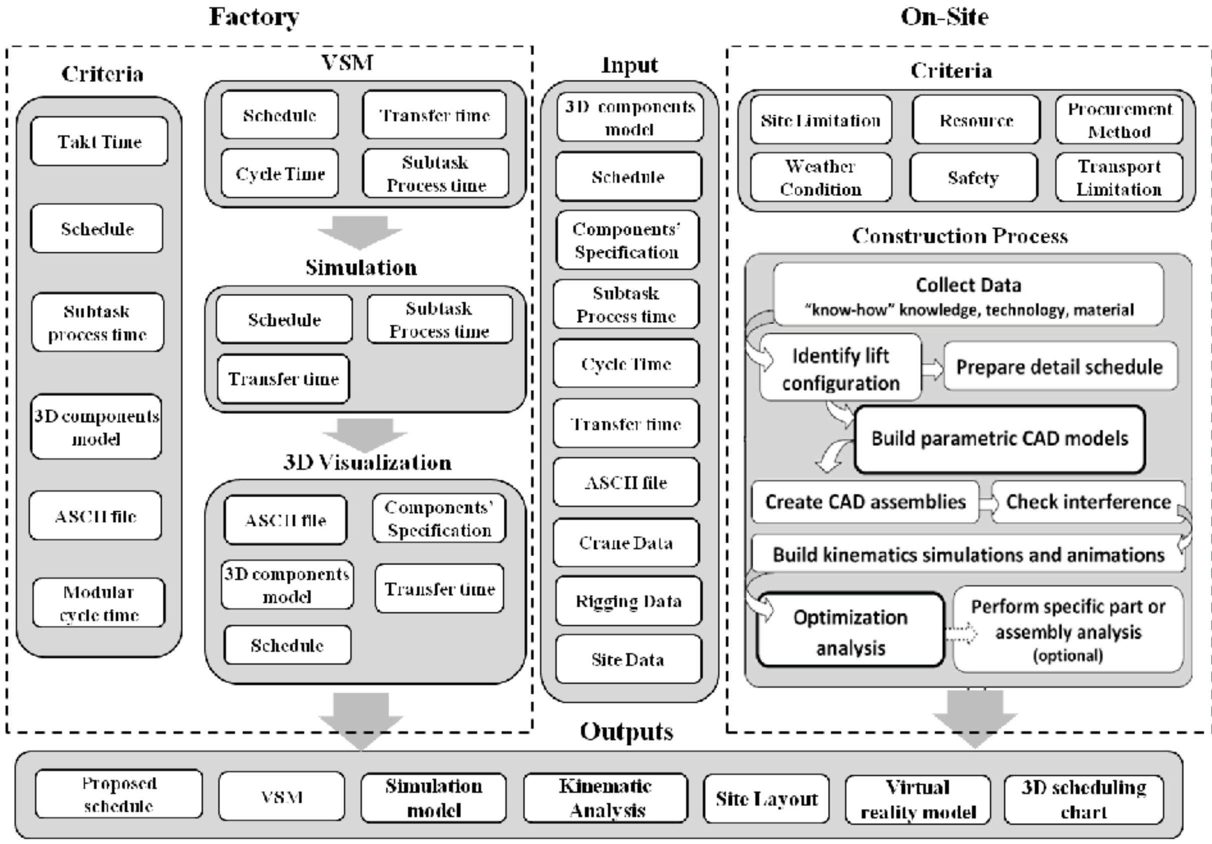


Fig. 1: Main Process of a Factory and On-Site

The proposed process of on-site called "construction process for crane operation" cannot function without input parameters which include components, crane and rigging data strictly related to equipment information, and site data. The crane data involves dimensions, radii, and lifting capacities related to boom length at specific radii. The construction process contains several activity blocks such as collecting data which is the core step in this process and refers to unique knowledge, materials, and technology. In the next step, particular crane configuration is established and a detailed schedule prepared. Based on presented information parametric CAD models, which describe objects' information, equipment, and site and obstruction models, are created. Models include properties and full size shapes of modules, transportation, site limitations, and resource availability to mimic real objects. The interference and clash checks performed during the construction process are critical since assembled modules cannot perform uninterrupted kinematics simulation and then animation steps. Simulation and animation outputs can be implemented independently at any time if the operator needs to analyze object displacement. The proposed process of on-site presented in this paper can be utilized for any project with no restrictions to the site layout. The virtual reality model describes the dynamic graphical depiction to assist decision makers in understanding the manufactured production line and crane operation on-site as well. It also predicts performance resulting from alternative decisions according to the work-space limitations and requirements, interference, clash, and the state of the proposed production process and crane operation which can increase costly site-errors and be time-consuming. The visualization can also be used as an advertising and education tool for workers and clients.

3. A Case Study

3.1 Visualization of the Production-line in the Factory Setting

Kullman Buildings Corp., located in Lebanon, New Jersey, has over 200 employees, which is one of the biggest modular building manufacturers in the United States. It has expanded its market to produce a variety of building types, including schools, equipment shelters, dormitories, multi-story residential buildings, correctional facilities, healthcare facilities, and US embassies. The Kullman shop mostly produces 12×30ft (350×914cm) or 12×20ft (350×609cm) standard modules with similar configurations and scheduling. The modules are delivered to construction sites to be assembled with other modules. According to the type of the module, the sequences and process times of the production process are different. In this paper, the focus was on the 12×30ft standard module assembly for a factory case. There are a total of eight stations and thirty-three tasks in the manufacturing production line. Each station has several tasks and workers. This paper used the proposed scheduling in the previous research (Yu 2008) instead of implementing a lean step. Based on the existing and proposed scheduling, two simulation models were built in Simphony software. The 50 modules as sample jobs and all required data, such as process time of each task, were loaded into the simulation models. Two results from the simulation models, average cycle time of each production line and process time of each task, were recorded, extracted, and analyzed. The process time of each task as input data for 3D visualization was automatically saved while the simulation was running. The average cycle time and productivity to produce 50 modules were used to validate the output of the proposed scheduling from the existing scheduling. Based on eight working hours per day, the cycle time in the proposed system was shorter than the original system, 2.32 working days. The productivity of the proposed system was improved to 1.58 modules per day from 1.47 modules per day in the original system. The simulation demonstrated that the proposed schedule was more effective than the old schedule. The simulation results may be smaller than real because of insufficient information collected. Figure 2 describes an example of simulation models and cycle time statistics. However, the simulation model could not provide space factors such as workers' collision and work-space limitation which may be occurred when the tasks are operated in the same place for the concurrent times. Visualization identifies these issues.

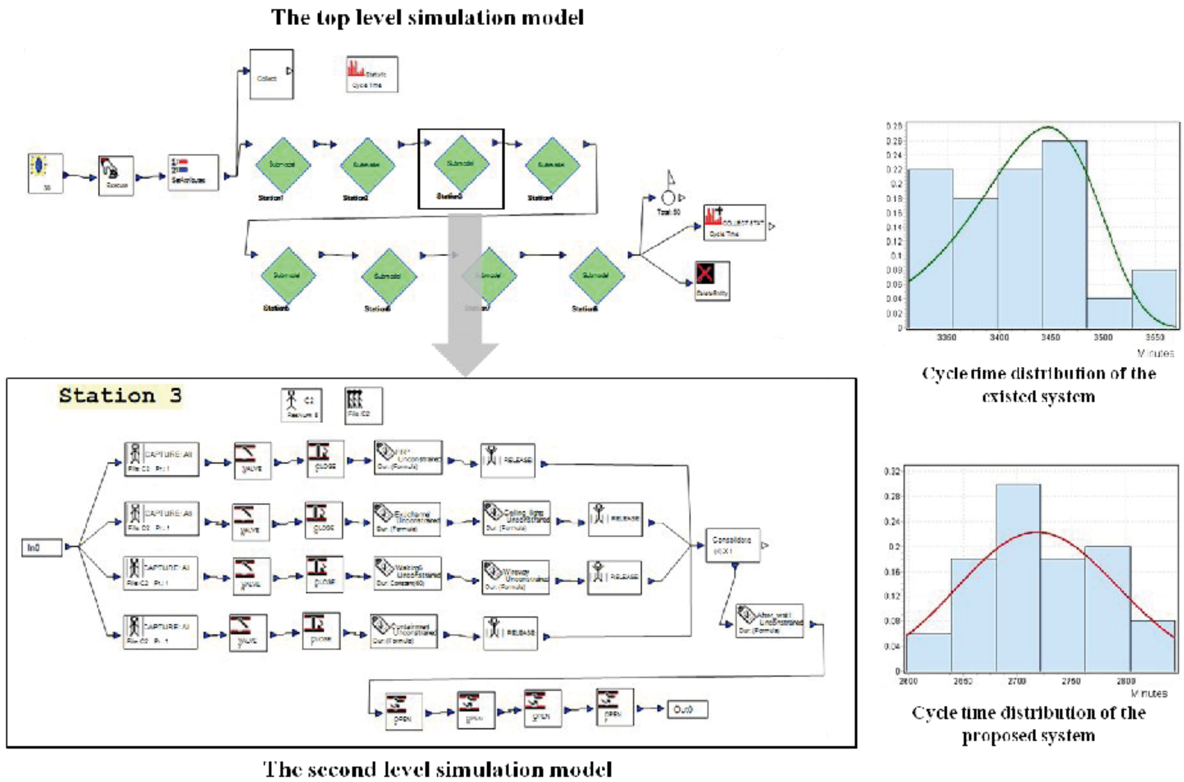


Fig. 2: An example of simulation models and results

The animation cycle for 3D objects includes delivery, installation, and movement back. Based on the animation cycle and ASCII file, the animation time was assigned to 3D objects in Maxscript. That is, animation for each 3D object was developed in each Maxscript file and then, these Maxscript files were combined to a main script file called Simulation-Animation Controller (S.A.C) including “Import” which inputs data into 3DS, “Delete” which removes all animation except 3D objects, “Reset” which builds new animation, “Play” which plays animation, “Stop” which pauses animation, and “Animation speed bar” which controls animation speed. It helps users to avoid repetitive works to develop the visualization without being time-consuming when the process time of each task is changed from the simulation model. The 3D bar chart related to each station was developed and animated while the animation in the same station was running. The state of tasks could be identified over the tasks' process times on a computer screen. The two capabilities of visualization in this case study, which could not have been identified by using simulation alone, were found: 1) the work-space requirements and limitations and employees’ accessibility for delivery, installation, and movement back to material, and 2) the operators’ collision when they work for the same process time in the same location. For example, the Station 4in the proposed schedules involved installing stenni with three carpenters, rough conduit and panel with two electricians in the equipment room, rough conduit with one electrician in the generator room, and start grounding with two grounders for five hours. The workers in rough conduit and panel, and start grounding tasks may have work-space conflicts and collisions because these tasks started and finished at the same time in the same places. The 3D visualization with various views monitored their process time, so that the proposed schedule in Station 4 could be adjusted. According to the monitoring, the work-space conflicts and accessibility problems were not found in Station 4. The cooperation of operators in Station 2 was implemented to save process time of the exterior drywall task and finish it within the required six-hour cycle time for each station. The 3D visualization described this cooperation when, after installing interior gypsum boards in the equipment room, two carpenters joined other carpenters who were finishing the drywall exterior. The work-space and collisions may be occurred in Station 2 because four operators worked for the same time in the same places. None of the problems were identified in 3D visualization. Figure 3 illustrates snapshots of Station 2, Station 3, and Station 4 animation with 3D bar charts. Consequently, the proposed manufacturing production line developed by lean production was accepted.

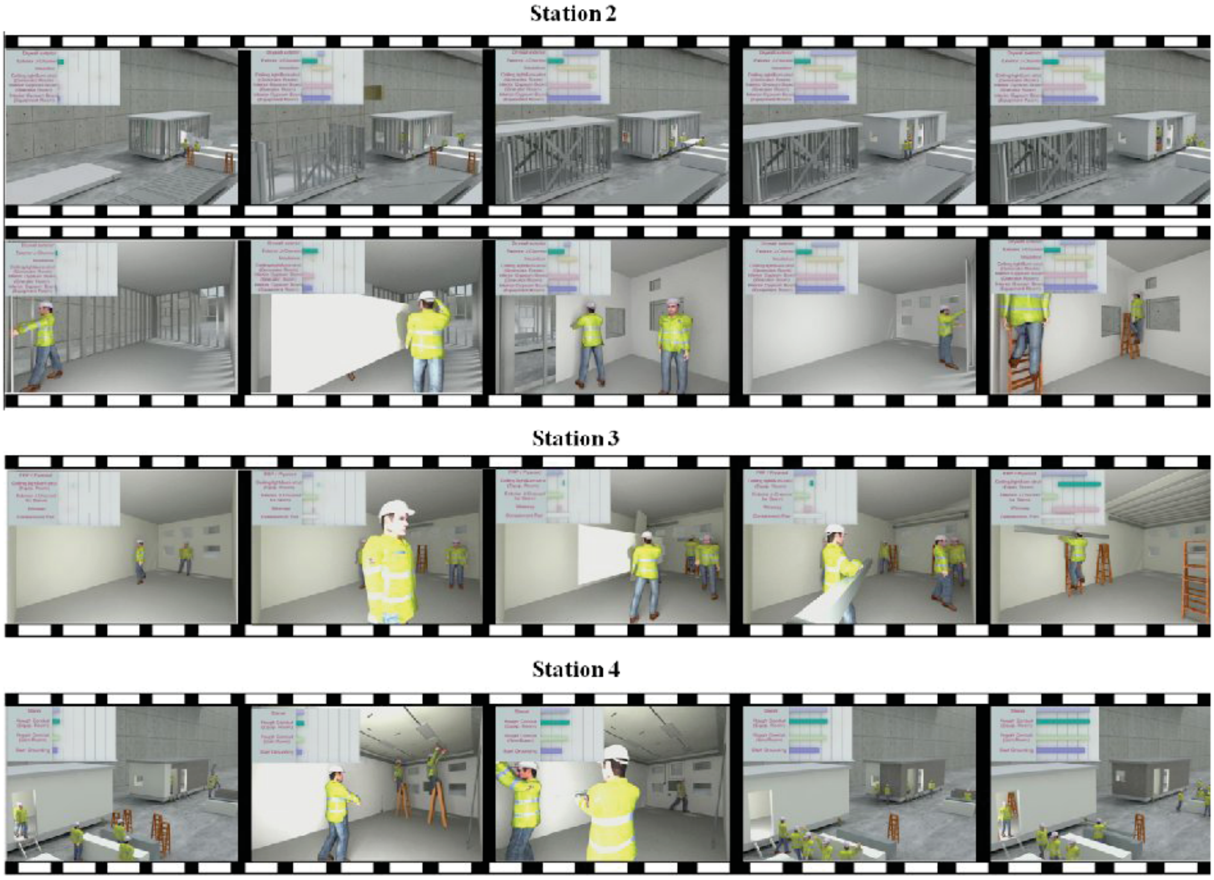


Fig. 3: Snapshot of 3D Animation with 3D bar chart

3.2 Visualization of On-Site Modular Assembly Operations

The modules, sized to fit standard flatbed truck trailers, were produced at Kullman shop and delivered to the Muhlenberg College in Allentown as on-site case study, and Pennsylvania for assembly into five new buildings. The three storey, 8,300 square-foot buildings, consisting of over ninety units placed together into five different building locations with the brick walls of the surrounding neighborhoods and housed 145 college students. Five dormitory buildings were arranged into two rows on a soft limestone hill, where slopes varied from 7 to 10°. Two access ways, the top and bottom of the hill, were available. Each of the buildings had six apartments, most with one double bedroom and three singles. Each building consisted of 18 modules, which met specific size and weight restrictions. The largest modules were 13 x 57 ft, weigh 72,000 lb. Figure 4 shows the required site and building information. The main construction constraint was that the five buildings must be built during the summer months. Therefore, the traditional on-site construction method, which required more time than the construction module method, was not considered. Manufacturing the units ahead of time, during the school year, at the factory floor assembly allowed the five buildings to be assembled on site in three weeks.

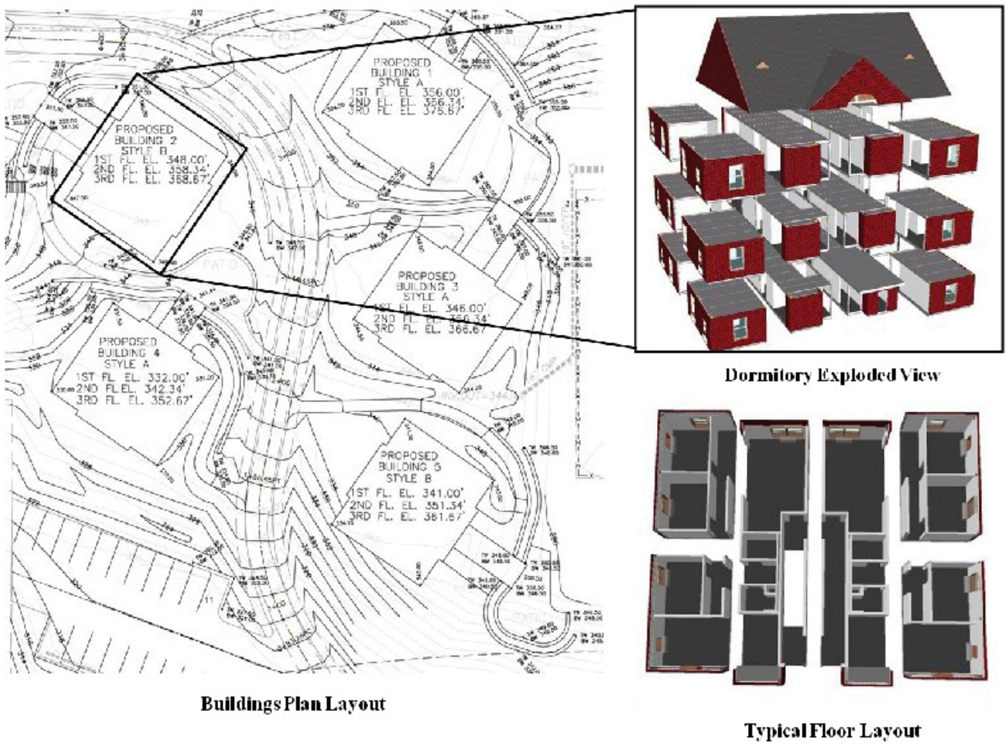
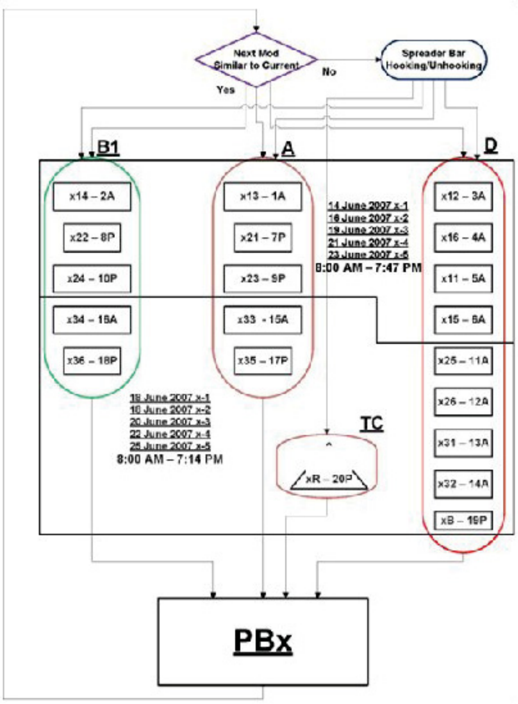
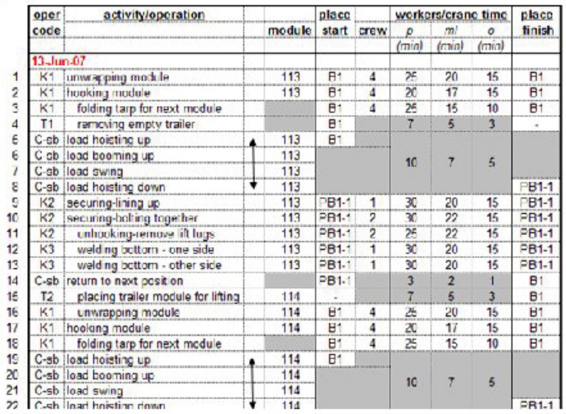


Fig. 4: Site and Building information

After collecting the required data, a detailed flow chart and daily schedules for crane operation, shown in Figure 5, were created. In the vertical columns of the flow chart, B1, A, and D describe the pick point areas. The rectangular boxes indicate delivered module code to the project: the first number relates to one of the five buildings, second floor and third floor module number, while the number after the dash represents the sequence of assembly. Suffix letters A and P indicate morning and afternoon operations, respectively. The outline of the flow chart (left in Figure 5) divides the modules into two separate days of lift operation. After the last lift operation, placing the preassembled roof on a building, was completed, the building was assembled in two days. The daily schedule of operation was created independently for each assembly day. It represented workers and crane time as "p, ml, o" values indicating pessimistic, most likely, and optimistic data, respectively. The triangular distribution input analysis simulation obtained these values. Accumulated data allowed the optimization of each assembly operation, and then the creation of the project Gant Chart schedule used in the visualization. Before field operation, the critical path was identified, and tasks involved in critical path procedures were carefully planned and checked. Using a crane selection algorithm (Al-Hussein 2005), the Demag AC 500-1 mobile hydraulic telescopic crane was chosen. The Center-of-Gravity moment effect algorithm (CoG) was used to optimize a lifting capacity of 600 tons (500,000 kg) to position modules. The mobile crane was operating with a maximum boom length of 183ft, the defined assembly sequence made the last lift operation critical: the 5th building's roof. During the entire assembly operation, only two rigging equipment configurations were used: 10-foot steel cables for small modules and 50 foot long spreader bar for roofs and large modules.





	oper code	activity/operation	module	place start	crew	workers/crane time p (min)	m (min)	o (min)	place finish
	13-Jun-07								
1	K1	unwrapping module	113	B1	4	25	20	15	B1
2	K1	hooking module	113	B1	4	20	17	15	B1
3	K1	folding tarp for next module		B1	4	25	15	10	B1
4	T1	removing empty trailer		B1		7	5	3	-
5	C-sb	load hoisting up	113	B1		10	7	5	
6	C-sb	load booming up	113						
7	C-sb	load swing	113						
8	C-sb	load hoisting down	113						PB1-1
9	K2	securing-lining up	113	PB1-1	1	30	20	15	PB1-1
10	K2	securing-bolting together	113	PB1-1	2	30	22	15	PB1-1
11	K2	unhooking-remove lift lugs	113	PB1-1	2	25	22	15	PB1-1
12	K3	welding bottom - one side	113	PB1-1	1	30	20	15	PB1-1
13	K3	welding bottom - other side	113	PB1-1	1	30	20	15	PB1-1
14	C-sb	return to next position		PB1-1		3	2	1	B1
15	T2	placing trailer module for lifting	114	-		7	5	3	B1
16	K1	unwrapping module	114	B1	4	25	20	15	B1
17	K1	hooking module	114	B1	4	20	17	15	B1
18	K1	folding tarp for next module		B1	4	25	15	10	B1
19	C-sb	load hoisting up	114	B1		10	7	5	
20	C-sb	load booming up	114						
21	C-sb	load swing	114						
22	C-sb	load hoisting down	114						PB1-1

Fig. 5: Flow chart and daily schedule (minute-by-minute) for crane operation (Jacek Olearczyk et al. 2009)

After the crane location was optimized, and the pick points for delivered modules secured, simulation was performed in Simphony software. The purposes of simulation were to provide the modules' lifting sequences, resource allocation and the timing operations of the assembly schedule. The material properties and texture mapping for visualization effect had been assigned to intelligent digital objects. Based on the data collected, 3D models were built to implement visualization. The separate detail crane site access analysis was performed to accommodate road width limits and allowable crane boom clearance. Assigning kinematic movement to each major crane component, and lift for each motion to time frame executes lifelike digital movies. Concatenation sets of separate hoist, swing, placing and returning operations create 3D animation. Placing each module at a defined time frame, allows one to recognize potential bottlenecks ahead of the actual construction. Other advantage of running animation several times, especially in the presence of the rigging crew, included the creation of mental pictures of planned activities which led to the prevention of costly site-errors and reduced construction time. The last, critical lift of the project (placing the roof for building 5) was virtually tested with many different options. Its complexity reinforced the fact that the crane boom was in conflict with already erected modules and was out of the operator's view. Performing virtual analysis allows the reconfiguration of the crane boom (added extension) and avoids problems during physical lift. Figure 6 shows animation snapshots for the construction operation, especially regarding crane operation. Implementation of 3D visualization decreased construction time from 21 days in the preliminary schedule to 10 days without sacrificing safety and quality.

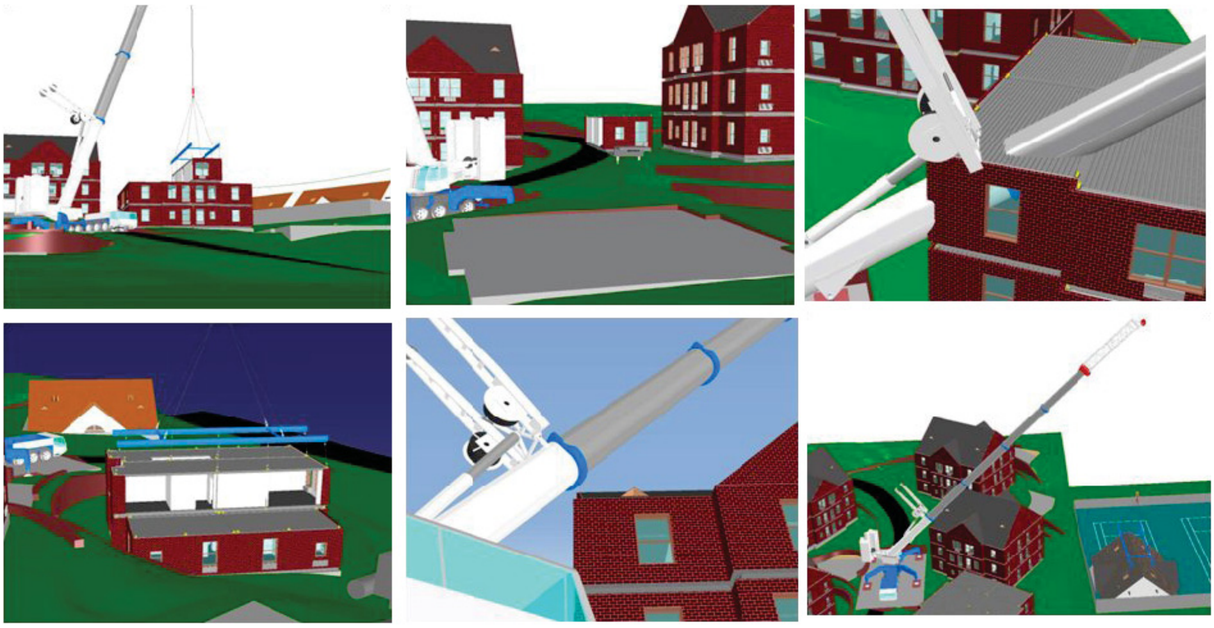


Fig. 6: Snapshot of animation for crane operation

4. Conclusion

The proposed methodology was implemented to validate and illustrate the effectiveness of 3D visualization with a factory and on-site cases respectively. A combination of simulation and 3D visualization provide important information which helps project managers better understand the effectiveness of changes made to the proposed production process and construction operation. Based on the simulation result, the visualization for the factory case using Maxscript was built in 3DS and described whether the work-space requirement and limitation, accessibility problems for operators, and inconsistencies in the level of detail among tasks with the 3D proposed schedules was identified. Although the visualization did not identify errors in the proposed schedule for the Kullman shop, it verified and validated lean and simulation results. It also increased the credibility of lean implementation plan. The project manager can use this system to experiment with the proposed scheduling to decrease rework, cost, site-error, and time before implementing it in the real-world. The on-site case study is a representative example which demonstrates the effectiveness of 3D visualization. In this case, visualization prevented accidents when the final lifting operation was implemented and reduced the project time from 21 days in the preliminary schedule to 10 days without sacrificing safety and quality, and the cost associated with planning and executing the lifts. The dynamic, graphical depiction of the visualization can be used as a marketing and education tool for potential customers and workers, respectively, to understand and introduce projects through its detailed information regarding material flow, crane operation, and the state of each task during the process time.

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HOOK TIME SIMULATION AND 3D-VISUALIZATION OF TOWER CRANE OPERATIONS

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ABSTRACT: *A well-organized, detailed schedule for crane operations requires the consideration of the construction schedule, on-site layout and possible collisions. Many on-site crane operations fail to meet the schedule requirements due to the lack of efficient schedule planning. To obtain a detailed schedule for crane operations, this paper presents a simulation model for hook time analysis. A simulation model integrated with 3D visualization allows users to imagine the expected evolution of building structures during a given construction period based on the schedule. To provide lift engineers with a planning tool, this paper presents a methodology to schedule the tower crane hook operations for high-rise building construction project using simulation and 3D visualization models. The proposed simulation model provides the realistic time required to perform each crane hook operation and presents the best possible lifting schedule. The proposed model is supported by a 3D model to visualize, verify and validate the crane lifting operations. A case study-based approach is used to demonstrate the effectiveness of the proposed methodology. This paper considers a tower crane with two jibs that operates using propellers mounted at the end of each jib which improve the performance of crane operations. The methodology has been tested in the planning process of the construction of a 34-storey building in busy downtown Brooklyn, New York, US. One of the challenges that have been investigated is the installation of over 1000-lifts that include over 950-modules. The proposed methodology provides the detailed crane schedule and the sequence of the scaffolding to complete the building from outside while modules are erected and floors are raised.*

KEYWORDS: *BUILDING CONSTRUCTION, SCHEDULING, 3D MODEL, HOISTING, LIFT ANALYSIS*

1. Introduction

A construction project's efficiency is determined by the effectiveness of the specific model used to communicate information. Advanced computer tools can be used to prepare smart designs which integrate simulation and visualization models to coordinate cross-disciplinary tools used for design, construction, and facility management decisions. Many on-site crane operations fail to meet the schedule requirements due to the lack of efficient detailed crane schedule planning. An efficient crane operation can have a significant positive impact on the overall scheduling, cost, and safety of a construction project. Poor design and improper crane selection contribute to most crane accidents on construction sites, and over 84% of all worksite fatalities result from improper crane use (Beavers et. al. 2006). Current research of construction cranes focuses primarily on developing tools to assist practitioners in the crane selection process (Sawhney and Mund 2002, Al-Hussein 2001, Hanna and Lotfallah 1999, Zhang et al. 1999). Usually, crane selection is based on the heaviest lift and/or the largest lift radius and the potential crane and picks position is identified by an experienced lift engineer. This method is time-consuming, does not check every potential lift scenario, and is not necessarily optimizing crane use. Al-Hussein et al. (2005), for instance, developed an optimization algorithm for selecting and locating mobile cranes on construction jobsites, using a series of 2D or 3D drawings to help engineers select and plan for mobile cranes. However, 2D drawing base approach has major limitations in identifying possible spatial conflicts related to dynamic crane operations (Tantisevi and Akinci 2008). Stability is an important safety issue related to crane use. Hasan et al. (2010-a) presented an integrated module to prevent crane accidents due to poor support design practices. Dynamic loading, regarding crane motion and load, are the key factors associated with the failure to maintain stability (Hasan et al. 2009-a). To reduce the dynamic effect on crane operation, the crane swing must be controlled effectively (Hasan et al. 2009-b). Many researchers have developed approaches to assist practitioners in optimizing site layout (Lim et al. 2005, Sivakumar et al. 2003, Tam et al. 2001, Chung 1999). Reddy and Varghese (2002) developed a tool using configuration space (C-space) to identify the crane lift paths and optimize the path within a constrained search space. These approaches identify the spatial conflicts at discrete time steps and at every location within the site boundary. 3D visualization is helpful in the verification and validation of crane operations (Al-Hussein et al. 2006) and can be a useful tool to improve the productivity of crane operation. Kamat and Martinez (2004) developed VITASCOPE for generating and displaying 3D animations of construction equipment based on a simulation model. Specifically, these visualization models with simulation show the cranes' expected locations at different times during the construction process (Akinci et al. 2003).

Tower cranes are widely used for the construction of high-rise and congested urban buildings. To obtain a detailed schedule for tower crane operation, this paper presents a simulation model for hook time analysis. The simulation module provides the realistic time required to perform each lifting operation and presents a best possible hook time schedule of all crane lifts. This information is supported by the 3D model for visualization, verification and validation of the lifting operations. The proposed methodology is applied the collaborative simulation and visualization to the area of tower crane operation in high-rise building construction.

2. Methodology

Practitioners schedule the tower crane activities as one of two main categories: primary or secondary. Typically, a tower crane operation focuses on the primary activity, such as the lifting module. Tower cranes can be erected in multiple configurations to yield various heights, reaches, and capacities. Crane hook time operations are based on a combination of three movements: hoisting, radial, and/or horizontal. Each lifting operation is broken down into separate hooking, lifting, swinging and horizontal activities as shown in Figure 1. As a result, the total cycle time for any given operation is calculated according to the Equation (1).

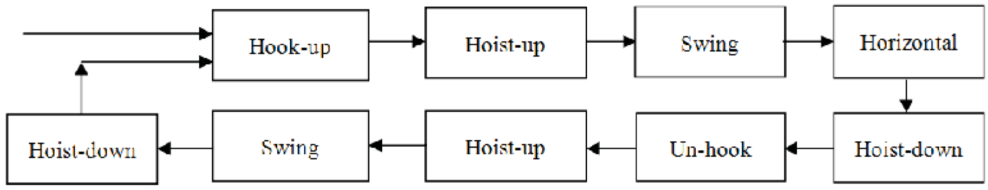

Fig. 1: Crane lifting activities

$$t_{cycle} = \sum_{a\in A} t_a + \sum_{b\in B} t_b = \sum_{a\in A} t_a + \sum_{b\in B} d_b / v_b \qquad (1)$$

where A and B represent the sets of static (e.g hook-up and un-hook), and dynamic (e.g. lifting, swinging, and lowering), activities occurring as part of the lifting cycle (see Figure 1). As for d_a and v_a, they refer to the load distance and velocity corresponding to activity *b*. Because of uncertainties, the parameters occurring in equation (1) will be described by appropriate probability distributions in the simulator, which will quantify the cost (in terms of time) of each sequence of activities. In addition to the uncertainties mentioned above, there are also variations in speeds for hoisting, radial, and horizontal trolley movements.

The proposed methodology is comprised of four components, as shown in Figure 2. The focus of this paper is on the improvement of tower crane operations, which include simulation, visualization, and productivity of resources. The simulation model provides an alternative analysis to perform the crane's lifting operation. To complement the simulation, visualization assists in determining the real time for each activity and improving the productivity of resources. The productivity model calculates the resource requirements and their utilization from both the simulation and visualization model and provides the most feasible option. The site geometry includes: (1) construction site layout, (2) building height (which evolves as the project progresses), (3) source location, (4) placing locations, and (5) obstacles (which also are dynamic in nature). The required information about load includes: size and shape, weight, and rigging requirements. Crane geometry and capacity information is obtained either from the manufacturers (technical specification manuals) or alternatively, from an existing crane database. The lifting operation process is based upon the following criteria: (1) safety, (2) lifting capacity, (3) priority of installation, (4) duration of each activity, and (5) cost. The model output includes the following four components: (1) suggested crane type, (2) best possible cycle time of each activity, (3) resource requirement and utilization, and (4) lifting schedule. This paper focuses on the process used to automate and minimize the activities associated with lifting operations of high-rise building construction.

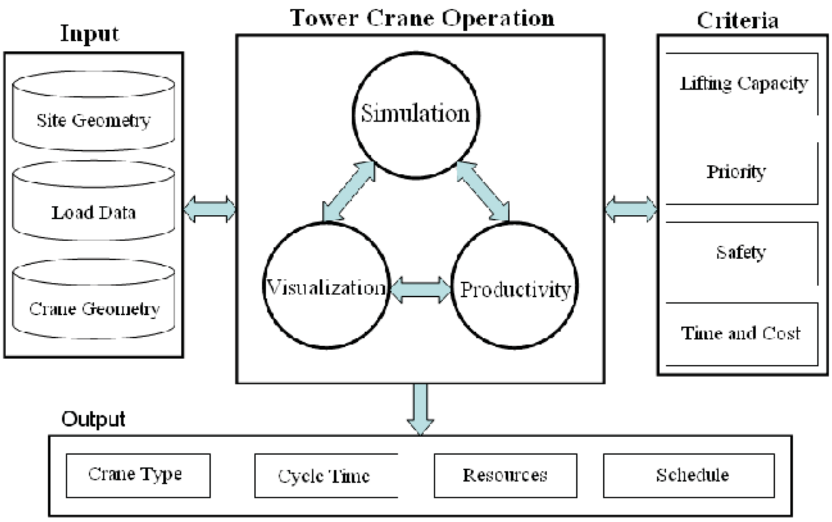

Fig. 2: Architecture of the proposed methodology

The proposed methodology considers a tower crane equipped with two jibs (Hasan et al. 2010-b) referred to in this paper as a 'double-jib' crane. The crane uses propellers mounted at the end of each jib, which reduce the energy used during their rotation. A double-jib tower crane has certain advantages. It increases the performance of crane operation by minimizing swing operation. If the angle between the source location and destination point is α, as shown in Figure 3, then when α < 90°, for the single and double jib crane, required rotation (R) can be calculated by satisfying Equation (2).

$$R = 2\alpha \qquad (2)$$

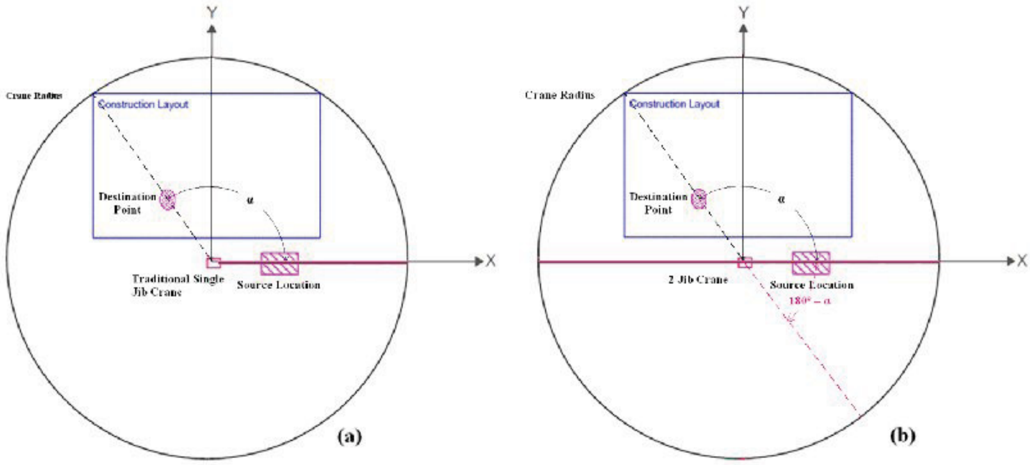

Fig. 3: (a) Traditional Tower Crane, (b) Double Jib Tower Crane

Again, in case of α >= 90°, for the single jib crane, required rotation can be calculated using the same Equation (2) where the maximum rotation is 360°; however, for the double jib crane, the required rotation (R) can be calculated by satisfying Equation (3).

$$R = \alpha + (180° - \alpha) = 180° \qquad (3)$$

3. Case Study

The proposed methodology has been tested in the case of a 34-storey modular building in downtown Brooklyn, New York, USA. Tall modular buildings have been successfully built as high as 24-storeys, but few have been erected in the US, and certainly none at the proposed height of 34 storeys. One of the challenges that have been investigated thus far is the logistics of installation of over 1000-lifts that includes over 950-modules and shear wall components in the busiest street in Brooklyn. The team will be challenged to maintain ambitious minutes-based schedules. The schedule challenges onsite include the logistics of sequencing the scaffolding to complete the building from outside while modules are erected and floors are raised. The general contractor decided to use a tower crane, either single or double jib, for transporting these module units from pick location to the installation location. The typical module construction using a tower crane is shown in Figure 4.

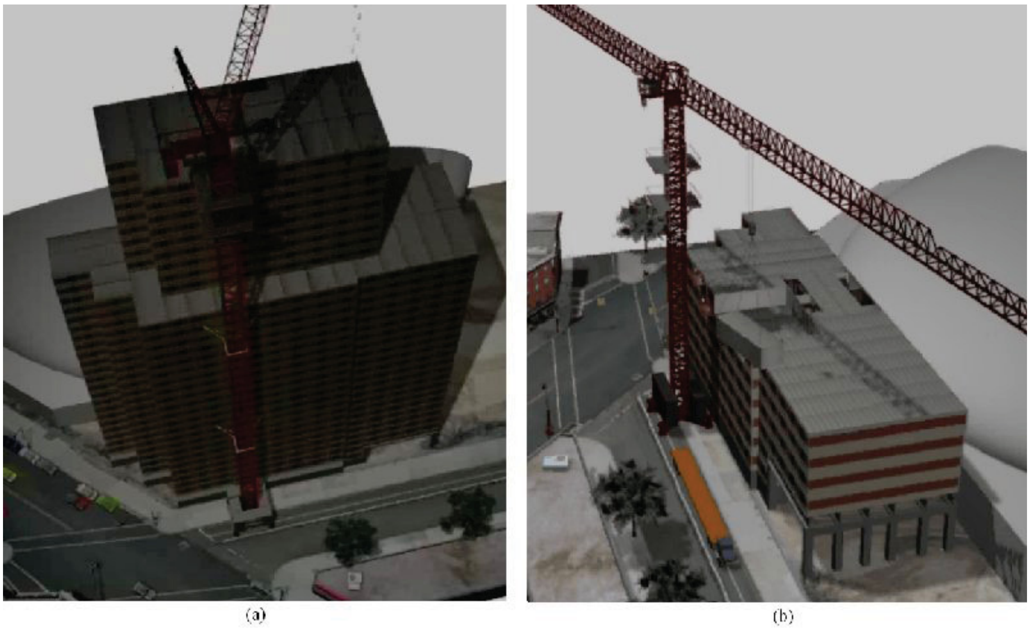

Fig. 4: 34-storey modular building construction using (a) single-jib tower crane, or (b) double-jib tower crane

Fig. 5: Hook-up activity using a platform

A tower crane is involved in various tasks, and is one of the most shared resources on construction site. Optimizing tower crane activities will increase the installation module per day. Other activities can be adjusted with crane operation by changing the resources in the simulation model. A visualization model for the activities is created based on scaled activity times. To minimize the duration of the hook-up activity, a platform is constructed up to the module height near the trailer arrival zone. The crew for the hooking process will wait on the platform, and as soon as the trailer arrives, they can start the hook-up activity, as shown in Figure 5.

The scaffolding operation for this type of modular construction is critical. Visualization of the scaffolding activity identifies any potential conflicts and minimizes the duration. Scaffolding is required in each module for bolting-welding activities. However, each module supplied with the scaffolding setup will be costly. Thus, it is decided that each day the first two modules will be supplied with scaffolding setup, and for the rest of the module, the scaffoldings will be transferred using the tower crane, as shown in Figure 6.

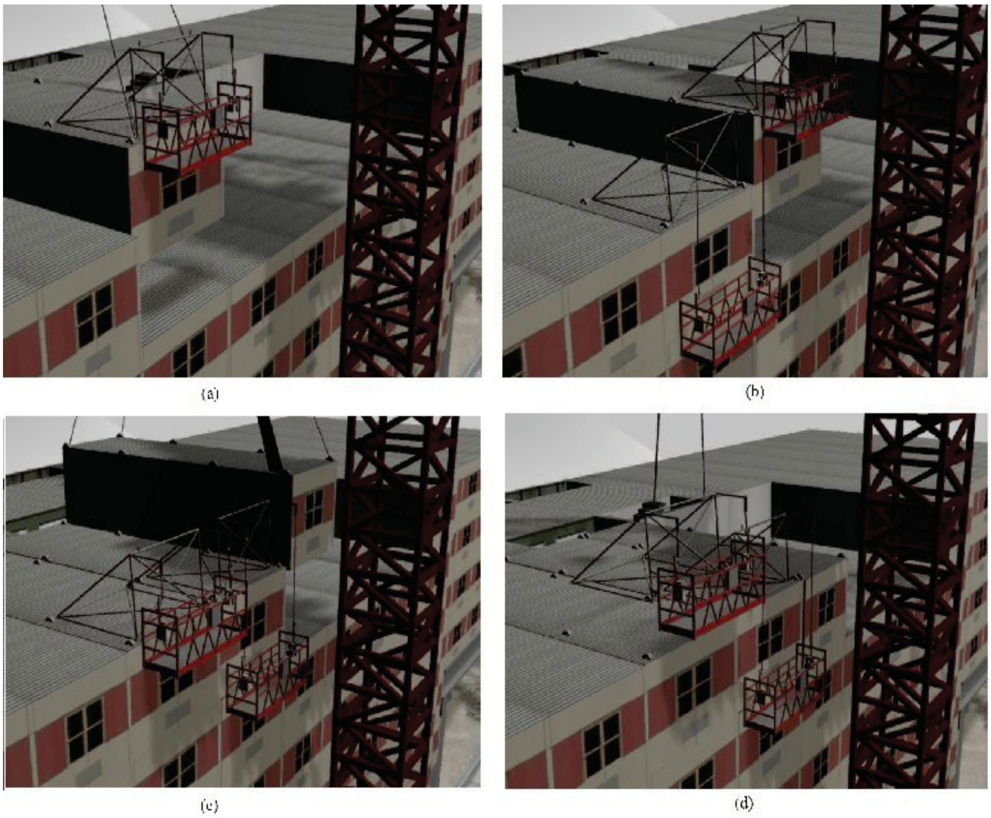

Fig. 6: Scaffold transfer from one module to another

A simulation model is developed using Simphony.NET3.5 (Hazzar and AbouRizk, 1999), as illustrated in Figure 7. In this model, all activity durations are analyzed within a triangular distribution (see Table 1), and five hundred minutes of working time a day are considered. However, workers are not required to work overtime; a total of 480 minutes (8 hours) of working time plus an hour lunch break is considered for each crew. The objective of the simulation model is to provide minute-by-minute schedules for crane operations. Some unpredictable factors such as wind may affect the crane operation. The effect of wind in crane operations for a particular project depends on the crane type and project location. Mobile crane operations are more vulnerable to high wind failures than those of tower cranes (Shapira and Lyiachin, 2009). Some guidelines set 50 km/h and 72 km/h as the safe wind speeds for mobile and tower crane operations, respectively (Watson, 2004; Construction Plant-hire Association, 2009). In the case study, both selected cranes are tower cranes, which have the advantage of usability in higher wind speeds; thus wind effect is ignored in this simulation model. However, wind gusts, instantaneous, maximum wind speeds usually lasting for less than 20 seconds (National Weather Services, 2011), can affect tower crane operations. In this case, the project manager or the crane operator may need to stop crane operations until it is safe to continue. The proposed schedule is also affected by traffic conditions, which may increase the time required to transport the module unit to the construction site. To keep the installation sequence flowing, a minimum of two trailers (loaded with ready modules) are required onsite to move delivered modules to the lifting zone. Ultimately, most of the crane activities vary based on the complexity of the work and the crew's performance and productivity. The swing module activity depends on the radial distance between the pick point of the module and the placing point, and the crane's swinging speed. Similarly, hoist up and hoist down activities depend on the hoisting speed of the crane with and without the load, and the floor height. For a 34-story building, the lifting height varies from 10 m to 110 m. Thus hoisting the module to the 34th floor (activity # 4) can take up to seven minutes. . Given that accuracy is an issue, the probability distribution which describes the ascending hoisting is updated for each floor.

Table 1 summarizes the possible duration for different types of activities associated with module installation at floor 2 using a single jib crane. Using a double jib crane one of the main advantages is that the second jib is always ready to take another load. Thus, double jib crane reduces the time of swing back of the jib and hoist down to take another load and it is considered in the simulation model (see Figure 7).

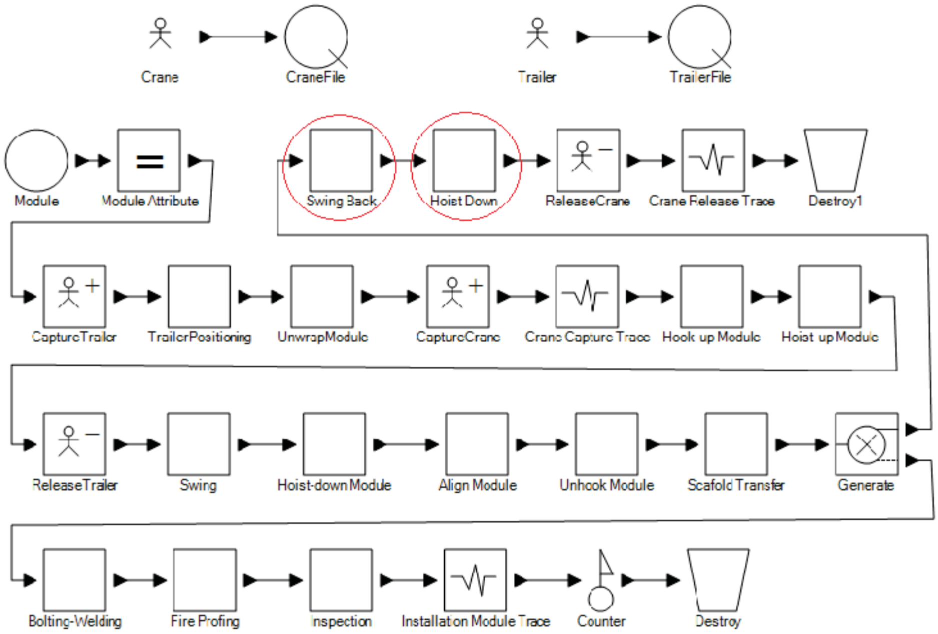

Fig. 7: Simulation Model from Simphony.NET3.5

Table 1: Possible duration for different types of activities using a single jib crane at floor 2

Activity #	Activity Description	Duration (min)		
		Pessimistic	Most likely	Optimistic
1	Trailer Positioning	2	1	0
2	Unwrap module	10	8	6
3	Hook-up module	5	4	3
4	Hoist up module	1	0.9	0.75
5	Swing module	1	0.75	0.5
6	Hoist down module	1	1	1
7	Align module	12	10	8

8	Unhook module	2	1	1
9	Scaffold transfer	6	5	4
10	Swing back to loading zone	0.75	0.5	0.4
11	Hoist down main line	0.5	0.4	0.3
12	Bolt/Weld module to structure	15	12	10
13	Fireproofing partition walls	15	12	10
14	Inspect installation	6	5	4

Using a single jib tower crane while satisfying all the required criteria, 20 modules can be installed per day at floor 2. For floor 33, using this crane operation sequence, 15 modules can be installed per day. Using a double jib crane, 22 modules can be installed per day at floor 2, and 17 modules can be installed per day at floor 33. Figure 8 illustrates the module installation per day on each floor using both crane types.

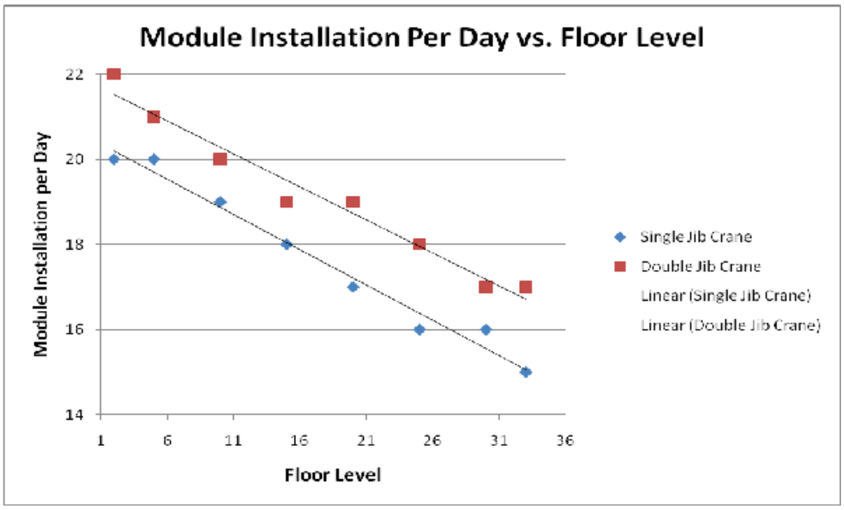

Fig. 8: Number of module installations per day at each floor level for both types of tower cranes

Although simulation models are routinely used in a variety of applications in science and engineering, it is instructive to calculate the average time corresponding to the case described in Table 1. For such a case, X_i is called as the random variable representing the time for activity *i*. As a result, the random variable X gives the total time for the fourteen steps, and can be expressed using Equation (4).

$$X = \sum_{k=1}^{14} X_k \tag{4}$$

Since the random variables occurring on the right hand side correspond to independent activities, the total average time can be calculated by satisfying Equation (5).

$$\langle X \rangle = \sum_{k=1}^{14} \langle X_k \rangle \tag{5}$$

Now, given that a triangular distribution profile is assumed for each task, the total mean time can easily be calculated with Equation (6)

$$\langle X \rangle = \sum_{i=1}^{14} \frac{a_i + b_i + c_i}{3} \tag{6}$$

where a_i, b_i and c_i represent the pessimistic, the most likely and the optimistic times, respectively. Now, using the above relationship, the expected time to install the first module in a day at the second floor is obtained immediately, that is $\langle X \rangle = 62.58$ minutes. As for the remaining modules, the installation time will decrease since some tasks are performed in parallel (see Figure 7). In fact, since the installation is crane controlled, the expected installation time for subsequent modules is calculated using the operation cycle of the crane, namely swing back, hoist down main line, hookup, hoist up, swing forward, hoist down, align, unhook and scaffold transfer. The use of the probability density functions describing such a sequence of activities (see table 1) in connection with Equation (6) yields the following mean installation time $\langle X \rangle = 23.91$ minutes. It is this time that is used to setup a schedule for all the modules ranked #3 or higher. The module # 1, 2 for a day comes with scaffolding setup; thus there is no need to transfer scaffold for that module which makes the installation time approximately 20 to 21 minutes for module # 2. Of course, simulation times may differ slightly but the differences should fall within the limits of the chosen confidence interval. Indeed, if the sequence of installation times given in Table (1) for the second floor using a single jib crane are considered, the 95% confidence interval for the mean installation time calculated (using the times corresponding to module #3 and on) can be written as follows:

$$\bar{x} - t_{\alpha/2,n-1}\frac{s}{\sqrt{n}} \leq \mu_X \leq \bar{x} + t_{\alpha/2,n-1}\frac{s}{\sqrt{n}} \Rightarrow 21.90 \leq \mu_X \leq 24.33$$

After validate the simulation model with the mathematical model a possible daily crane lifting schedule for different floor using both type of cranes is prepared. Table 2 summarizes the start and finish time of a working day with the installation complete time of each module at the 2nd and 34th floor for both types of crane.

Table 2: Typical module installation schedule on a day at 2nd and 34th floor using single or double jib crane

Single-Jib Crane				Double-Jib Crane			
2nd Floor		34th Floor		2nd Floor		34th Floor	
Module	Time Installed	Module	Time Installed	Module	Time Installed	Module	Time Installed
(Start at 7:40:00 AM)							
1st	8:40:00 AM	1st	8:45:00 AM	1st	8:35:00 AM	1st	8:40:00 AM
2nd	9:00:00 AM	2nd	9:16:00 AM	2nd	8:54:00 AM	2nd	9:05:00 AM
3rd	9:23:00 AM	3rd	9:47:00 AM	3rd	9:15:00 AM	3rd	9:33:00 AM
4th	9:46:00 AM	4th	10:18:00 AM	4th	9:36:00 AM	4th	10:01:00 AM
5th	10:09:00 AM	5th	10:49:00 AM	5th	9:57:00 AM	5th	10:29:00 AM
6th	10:32:00 AM	6th	11:20:00 AM	6th	10:18:00 AM	6th	10:57:00 AM
7th	10:55:00 AM	7th	11:51:00 AM	7th	10:39:00 AM	7th	11:25:00 AM
8th	11:18:00 AM	-	Lunch Break	8th	11:00:00 AM	8th	12:53:00 AM
9th	11:41:00 AM	8th	1:22:00 PM	9th	11:21:00 AM	-	Lunch Break
10th	12:05:00 PM	9th	1:53:00 PM	10th	11:42:00 AM	9th	1:21:00 PM
-	Lunch Break	10th	2:24:00 PM	11th	12:03:00 PM	10th	1:49:00 PM
11th	1:28:00 PM	11th	2:55:00 PM	-	Lunch Break	11th	2:17:00 PM
12th	1:51:00 PM	12th	3:26:00 PM	12th	1:24:00 PM	12th	2:45:00 PM
13th	2:14:00 PM	13th	3:57:00 PM	13th	1:45:00 PM	13th	3:13:00 PM

14th	2:37:00 PM	14th	4:28:00 PM	14th	2:06:00 PM	14th	3:31:00 PM
15th	3:00:00 PM	15th	4:59:00 PM	15th	2:27:00 PM	15th	3:59:00 PM
16th	3:23:00 PM			16th	2:48:00 PM	16th	4:27:00 PM
17th	3:46:00 PM			17th	3:09:00 PM	17th	4:55:00 PM
18th	4:09:00 PM			18th	3:30:00 PM		
19th	4:32:00 PM			19th	3:51:00 PM		
20th	4:55:00 PM			20th	4:12:00 PM		
				21st	4:33:00 PM		
				22nd	4:55:00 PM		

The analysis shows that the double-jib tower crane operation uses resources more efficiently than a single jib crane. Table 3 summarizes the number of crew required for each activity, start time and finish time and percentage of working time used by each crew for both types of crane operation at floor 2. The loading zone crew's main responsibility is to un-wrap the module when delivered and assist in hook-up the module in the loading zone (pick point) of the module. On building zone crews are required to assist in un-hooking, aligning and positioning the module and managing scaffolding hook and un-hook operations. From Table 3, it is found that loading zone crews are using only 54% of their working hours. These crews can be used for other activities at the loading zone, if required, without any effect on the module installation schedule. On building crews use around 70% of their working hours. Thus, if they are required to do any extra activities, it may create a delay in the installation process. The focus of the developed simulation and visualization model is to optimize the activities which depend on crane and provide time and location schedules for these activities. For each crew, the job and location will be pre-determined as per the schedule. Crews will not seek out work; jobs will be assigned, and work will come to them.

Table 3: Utilization of different type of resources at floor 2

Crew Type	No.	Start	Finish	Available Time (min)	Active (min)	Idle (min)	% of Utilization
Single Jib Crane							
Loading Zone	4	7:40:00 AM	4:40:00 PM	480	260	220	54%
Crane Operator	1	7:45:00 AM	4:45:00 PM	480	457	23	95%
On Building	6	7:50:00 AM	4:50:00 PM	480	320	160	67%
Bolt and Welding	4	7:55:00 AM	4:55:00 PM	480	300	180	63%
Fireproofing and Inspection	4	8:00:00 AM	5:00:00 PM	480	400	80	83%
Double Jib Crane							
Loading Zone	4	7:40:00 AM	4:40:00 PM	480	286	194	60%
Crane Operator	1	7:45:00 AM	4:45:00 PM	480	472	8	98%
On Building	6	7:50:00 AM	4:50:00 PM	480	352	128	73%
Bolt and Welding	4	7:55:00 AM	4:55:00 PM	480	330	150	69%
Fireproofing and Inspection	4	8:00:00 AM	5:00:00 PM	480	440	40	92%

4. Conclusions

This research aimed to develop an algorithm to assist practitioners to plan detailed schedules for crane operations integrated with 3D visualization. Planning crane operations, especially in regards to the sequence of crane hooking operations, will eliminate delays and the potential hazards of crane usage on construction sites. Visualization of the hooking operation could be shared with the crane operator, the lifting crew and engineers, which would help eliminate potential conflicts between objects and cranes. Two types of tower crane, single jib and double jib, are analyzed using the proposed methodology for the construction of 34-storey modular building. Results show that using a double jib is more efficient than using a single jib crane. However, the final selection of the crane depends on the management policy, crane ownership, crane availability and its technical support. Researching more effective ways to operate cranes will allow the construction industry to establish best practices.

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APPLYING RBF NEURAL NETWORKS TO REDUCE LOCALIZATION ERROR OF WIRELESS SENSOR NETWORKS

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ABSTRACT: *Timely acquisition of construction resource information is an essential task for construction engineers and managers. In recent years, Wireless Sensor Networks (WSN) have emerged as a promising means to improve current construction localization applications due to the ease of deployment and expandability on large scale construction projects, low cost, and capacity to function efficiently under dynamic and rough environments. Received Signal Strength Indicator (RSSI) based localization is an increasingly popular choice, especially for indoor scenarios using WSN. The fundamental requirement of such localization systems is to infer the position of a mobile node at a particular location from the RSSI which are perceived by a limited quantity of sensor nodes in the network with known coordinates. However, the problem of fluctuating RSSI due to multipath propagation effects, along with the unavailability of wireless signals at some site locations, compounds the application of such localization techniques on construction sites. To effectively reduce the uncertainty and the localization error of wireless sensor networks, we propose a real-time error correction approach that leverages the strengths of wireless sensor networks and Radial Basis Function Neural Networks (RBF NN). A field experiment shows that RBF only entails the use of a very limited set of known-points and can decrease the localization error from 1.11 m to 0.57 on average. The proposed solution will be flexible and cost effective for industrial construction settings (fabrication shop or module yard) where GPS is not reliable. Real time data of the current dispositions of equipment and labour resources and various work-items will be organized in a database. The database provides geo-coordinated data for resource or component visualization in Augmented Reality (AR) or Mixed Reality (MR), laying the infrastructure for future development of on-line planning and control systems.*

KEYWORDS: *Location Aware Computing, Wireless Sensor Network, Radial Basis Function Neural Network, Received Signal Strength.*

1. Introduction

In recent years, localization and tracking technologies have stimulated research efforts directed towards automated resource tracking and data acquisition for monitoring and improvement of construction processes (Jang and Skibniewski 2009). Project success critically depends on effective management of construction resources, including workforce, equipment, and materials. The completion of project tasks on schedule, safely, and with the planned budget needs an organized planning effort that allocates adequate availability of project resources (Teizer 2008).Therefore, the level of awareness of resource status or project performance can have a significant impact on successful completion of construction projects. In fact, timely information about these factors can assist in fast and confident real-time decision making. Due to the need for reliable solutions for real-time asset localization and resource tracking in the dynamic environment of construction sites, many research efforts have been made to develop a reliable framework for facilitating the application of these technologies (Goodrum et al. 2006, Song et al. 2006, Ergen et al. 2007, Teizer 2008, Khoury and Kamat 2009, Jang and Skibniewski 2009).

In recent years, the interest and need for indoor localization has also been rapidly increasing in the construction area (Khoury and Kamat 2009). Construction tasks, including inspection and progress monitoring, need to have access to project information in indoor or partially covered environments, such as tunnels, fabrication shops and buildings under construction. Outdoor localization methods have been developed and deployed, but indoor techniques remained a research challenge. The Global Positioning System (GPS) is an attractive option for outdoor environments, but is not suitable for indoor applications because its positioning mechanism requires that any location to be fixed should have line-of-sight with at least 3 satellites. In addition, due to the complexity of indoor environments, the development of an indoor localization technique is always hindered by a set of challenges such as the dense multipath effect, lack of line-of-sight, noise interference and building material dependent propagation effects (Zhang et al. 2010). The application of technologies such as Radio Frequency Identification (RFID) and Ultra-Wide Band (UWB) has been suggested to date for dynamic indoor position tracking. However, they have not yet been proven effective in support of accurate tracking frameworks developed for large-scale dynamic construction projects. Wireless sensor networks (WSN) have also emerged as a promising means to improve current applications of RFID in construction due to the ease of deployment and expandability on large-scale construction projects, the lower cost, and the capacity to work efficiently under dynamic and harsh environments (Shen et al. 2008, Jang and Skibniewski 2009).To address the limitation of RF (Radio Frequency) technologies, recent construction research has explored the opportunity of developing cost-effective positioning methods by evaluating the received signal strength. In particular, with the use of the low-cost WSN technology, RF-based real-time positioning solutions can be easily designed and deployed (Haque et al. 2009).

In this study, a new positioning framework is proposed which relates position with the strength of received radio frequency signals, so as to facilitate the localization of construction resources in both indoor and outdoor environments. By deploying an extensible wireless sensor network, the received signal strength indicator (RSSI) method coupled with the positioning architecture and artificial neural network computing will be used to lock the position of a mobile sensor node (attached to a resource) in relation to stationary sensor nodes. The positioning system collects signal strength readings from a limited set of known locations and stores such data in a database during a WSN profiling stage. Subsequently, the problem of estimating the location of a mobile node emitting an RF signal from an unknown place boils down to applying a data mining technique, which selects a best matched set of profiling points and then averages the coordinates of those points into an approximate location of the mobile sensor node being tracked. An RBF based approach is proposed to correct the wireless sensor network positioning error in real time.

2. BACKGROUND

Over the past decades, with the help of advanced computer and sensor network technologies, it has become practical to increase the efficiency of data collection and communication methods at construction sites. Field data collection and communication techniques have become more efficient in construction areas with the help of advanced computer and localization methods. The information enables construction managers to be aware of the current state of construction resources. For many years, Radio Frequency

Identification (RFID) systems and the Global Positioning System (GPS) have been the predominant technologies for automated tracking and monitoring of construction assets (Goodrum et al. 2006, Teizer et al. 2007, Lu et al. 2007), outperforming previous technologies such as barcodes and providing effective support for resource positioning, tracking, and automated data collection in construction. However, there is a wide range of limitations to positioning approaches which utilize these technologies in construction applications.

RFID does not meet requirements for harsh construction conditions as a result of inaccurate positioning (Pradhan et al. 2009), inflexible and limited networking capabilities, and the high cost of RFID readers (Skibniewski and Jang 2009). Moreover, the communication distance between RFID tags and readers is significantly affected by surrounding metals, concrete and moisture and this reduces the performance of the technology (Ergen et al. 2007). Current stand-alone GPS can provide locations in open areas with accuracy of around 10 m. Real-Time Kinematic GPS (RTK GPS) can further improve positioning accuracy up to centimeter levels by applying special algorithms to process the carrier phase measurements of the GPS signals from both single station base and mobile receivers. On the other hand, the performance of GPS localization system can be considerably decrease on the dynamic construction site due to blockage and the multipath effect, which is caused by deflection and distortion of satellite signals in highly dense areas or by temporary structures or facilities such as hoarding, scaffold and formwork (Lu et al. 2007).

In order to overcome the limitations of traditional monitoring systems, there has been growing research interest in exploring the utilization of WSN in recent construction applications. A WSN is a self-organizing network composed of a large number of sensor nodes which closely interact with the physical world. It features low-cost sensors, extensible network capability allowing deployment of large quantities of nodes so as to increase the network coverage, stability, and communication reliability. In addition, low power consumption facilitates operation and maintenance of the system (Shen et al. 2008).

In this study, an RSSI-based indoor localization scheme (Haque et al. 2009) was utilized for wireless sensor network-based positioning and tracking applications in construction sites. The simplicity and accuracy of this positioning approach made it a good candidate, with a reported localization average error well below 1 m in indoor environments. In addition, the uniformity and low cost of the equipment make it a highly viable and very practical solution. However, this scheme has not yet been convincingly substantiated by experiments in real indoor environments involving elaborate configurations of practical scenarios, including obstacles, walls and dynamic environments. Therefore, an indoor experiment was conducted in order to evaluate and confirm the capability of the RSSI-based positioning architecture in real scenarios. To improve the accuracy of the location-aware system based on RSSI, a Radial Basis Function (RBF) Neural Networks technique has been employed. The difficulty in quantifying the impact of indoor wireless signal propagation on localization accuracy has made Neural Networks (NN) an appropriate technique for quantifying this effect so as to reduce the localization error. The effectiveness of the proposed integrated system was then assessed in an indoor case study to evaluate the potential for construction resource tracking in real project sites.

3. Architecture of the Positioning Algorithm

The localization research attempts to solve the problem of determining the location of a node within its environment. Localization algorithms can generally be divided into three categories: Range-based, Range-free and RSSI profiling. The range-based method estimates the distance or angle between the transmitter and the receiver. In RSSI profiling technique, the perceived characteristics of the tracked tag's signal are compared against pre-collected samples from known locations. Finally, the range-free method is also defined exclusively by the perceived connection between the tracked tag and its neighbors. The range-based method depends greatly on line-of-sight communication and requires expensive infrastructure. It also suffers from the presence of different materials, equipment, and building structures at construction sites. As such, RSSI and range-free methods are considered to be more suitable for localization applications on building construction sites. The majority of positioning systems employed the RSSI owing to its broad accessibility in wireless radio signal communication (Lymberopoulos et al. 2006). In addition, solutions in range-free localization are identified as a more cost-effective alternative to the range-based approaches for large scale sensor networks (He et al. 2003).

The localization architecture called LEMON uses an RF-based localization scheme [14] which operates based on sensing the strength of the received RF signal and is a combination of a range-free method and RSSI profiling. This architecture is simpler and more accurate than other approaches and the uniformity and low cost of devices makes it a highly viable and very practical solution for construction. The infrastructure nodes of the proposed localization architecture are low-cost, low-power wireless devices [EMSPCC11 by Olsonet Communications (Olsonet Communications Corp, 2011)]. The node makes use of the CC1100 RF module from Texas Instruments, operating within the 916MHz band. From an operational point of view, the node is called a "peg" when it captures signal strength. The pegs' locations are fixed (static nodes) and their precise location need not be known. A monitored device, which is a node of the same type as a peg, is called a tag.

The process of location estimation in LEMON consists of two phases: profiling and actual localization. Generally, during operation in both phases, a tracked tag periodically emits RF packets. In the profiling stage, tags are located at predetermined known locations called reference points. LEMON maintains a database of signal strength readings from tags on a central server. In this phase, all the pegs that can "hear" the RF packets emitted by the tags will forward the data as a report to the central server. The database consists of samples which are stored as Triplets $< C;\Omega;\tau >$ in which represents the known coordinates of the sampled point, Ω stands for the association set (which comprises peg ID and the RSS value received by that Peg), and symbolizes the class of sample, identifying the RF parameters of the transmitter (such as transmission power, bit rate, and channel number). The process of actual localization of the tracked tag is similar as the profiling stage. The only difference between the profiling phase and actual localization is that, in the profiling stage, the association set of tag profiling reports also includes the known coordinates of the sampled point, but in the actual localization stage, the location of the tracked tags needs to be estimated based on the location of sampled points.

In the localization stage, the server compares the perception of the tracked tag's RSSI measured by all the pegs in the monitored area and the RSSI of each profiled reference point and evaluates the difference between the tag and all the profiling points. If $\Omega = \{w_1,\ldots,w_k)$ and $\Psi = \{\psi_1,\ldots,\psi_k)$ are assumed to be two association's sets, the distance between these sets will be:

$$D(\Omega,\Psi) = \sqrt{\sum_{j=1}^{N}(R_{\Omega}(j) - R_{\Psi}(j))^2}$$

where is the total number of Pegs in the network and is defined as , if the pair occurs in Ω , and 0 otherwise. Therefore, the server evaluates the distance of each pre-selected sample (its association set) from the tag's association set representing the combined momentary perception of the tag's RSS by all the pegs that can hear it. Then it selects an arbitrary number k of profiled samples with the smallest distance from the tracked tag, which is called a best matched set of profiled points. Subsequently, the coordinates of the selected samples are averaged to produce the estimated coordinates of the tag. The averaging formula biases the samples in such a way that the ones with a smaller distance contribute with a proportionally larger weight.

If we assume that is the maximum distance among the best selected samples and is the sum of all those distances, thus, the tag coordinates are estimated as:

$$x_{est} = \frac{\sum_{i=1}^{k} x_i \times (D_{\max} - D_i)}{K \times D_{\max} - S_d}$$

$$y_{est} = \frac{\sum_{i=1}^{k} y_i \times (D_{\max} - D_i)}{K \times D_{\max} - S_d}$$

where $(x_i - y_i)$ are the coordinates associated with sample . Note that in this approach, RSSI is only used as a numerical attribute of a profile sample whose value should be close to the perceived value.

To evaluate the environmental variation due to the presence of an obstacle on the performance of the proposed system, a prototype system was previously assessed in an indoor environment (Soleimanifar et al. 2011). To mock the situations commonly encountered in construction sites, a car was placed in the testing area, partially obstructing the radio signal paths between sensor nodes. It was found that the localization accuracy in the presence of obstacles remained comparable to that achieved prior to the introduction of obstacles. The robust nature of this localization technique thus implied its potential for deployment in real-world dynamic construction sites. Those settings by nature are prone to constant changes as a result of the presence of permanent as well as of temporary obstacles. Additionally, RSS values might not be available at some locations all the time. Since the positioning reliability and accuracy is directly affected by the quality of sample wireless signal data collected at target locations, we managed to collect an adequate quantity of RSS samples at each target location. In our experiments, we observed that the cases of inaccessible points were rare. In such cases, the inaccessibility at a given access point could also occur on adjacent profiling samples. Thus, that proposed methodology employed a statistical learning approach in order to tolerate a certain amount of noises (such as unavailable RSS signals) in fixing a tag's position.

The proposed WSN based positioning method provides an "ad hoc" solution for a particular application purpose and application setting. The experiments were designed to mimic the movement of a laborer on a building construction site who performs repetitive wall form-working activities. Note the laborer's movement generally follows certain patterns (not totally random). Such patterns make it possible to carefully design and deploy a layout of pegs, which ensures the radio signals are available at the majority of peg sensor locations.

4. Error Correction Algorithm Using Radial Basis Function

Inside the building, radio signal propagation follows a complex model due to Non Line of Sight multi-path effects caused by the building materials, human body absorption, neighboring devices and metal and dynamic nature of environment. Due to these limitations, indoor location estimation becomes a complex problem and is difficult to engineer using classical mathematical methods. Therefore, raw RSSI does not provide sufficient accuracy for location systems due to high fluctuations of the received signal over measuring time (Lymberopoulos et al. 2006).

To improve the accuracy of the location-aware systems based on RSSI, several techniques have been employed, including Bayesian classification and filtering, K-Nearest Neighbors, GPS-like triangulation and Kalman Filtering. However, these approaches have not yet been proved for indoor localization applications, since indoor wireless signal propagation is so complex and indefinable that it is still hard to attain a steady accuracy level.

Ahmad et al. compared the results of previous research in indoor positioning techniques and found Neural Network overall provides a better solution to the location determination problem. For instance, Kalman filtering is applicable to error correction on the next position in addressing "inertial navigation" problems which generally apply instrumentation for positioning (gyroscope or compass): time-dependent patterns in positioning errors on previous positions can be represented by a steady noise distribution. Shareef et al. (2008) conducted an RSS-based localization method using Kalman filtering and Neural Networks, observing better performances with RBF neural networks in terms of accuracy based on experimental results. Compared with Neural Networks, Kalman filter made fewer mistakes but produced larger magnitude of errors especially on the boundaries of the testing area.

Note in contrast with the Kalman filters, Neural Networks perform well only for the area in which they have been trained. In other words, if the tracked object passes beyond the boundaries of the area where the neural network model has covered, the neural network will not be able to localize the tag with reliability. As previously mentioned, the proposed WSN based positioning method provides an "ad hoc" solution for a particular application purpose. The WSN coupled with RBF NN provides a cost effective infrastructure for real time re-profiling and re-calibration of the positioning solution on a continuous, real-time basis. For instance, to cope with the dynamic nature of the working environment, the WSN-RBF can be automatically recalibrated at a preset frequency (once per ten minutes or every half an hour).

The Kalman filtering technique iteratively refines the position estimates of an object in a continuous motion path over time based on the noise parameters that follow a Gaussian distribution. The Kalman filter uses the laws of kinematics to predict the location of the tracked object, requiring several iterations before it begins to reach the accuracy of the Neural Network (Shareef et al. 2008). For Radio Frequencies based positioning (RSS), the position errors may not exhibit continuity over time and space as the collected RSS data are likely to contain many "outliers". This can render applying the Kalman filtering to be ineffective. The proposed RBF NN method for error correction is more tolerant of potentially substantial fluctuations in the RSS results associated with two consecutive positions of a moving object.

The difficulty in quantifying the impact of indoor wireless signal propagation on localization accuracy has made Neural Network (NN) an excellent technique for quantifying this effect, to reduce the localization error. Radial Basis Function (RBF) NN is preferred over the classic back-propagation (BP) algorithm due to two factors: 1) RBF's training time is short and deterministic; and 2) the RBF algorithm is free from local minimum trap and overtraining (Shareef 2008).

The radial basis function (RBF) neural networks consist of neurons which are locally tuned and attractive due to their fast training and simplicity (Fasshauer 2007). Fig. 1 shows the basic RBF neural networks that consist of three layers: an input layer, hidden layer and output layer.

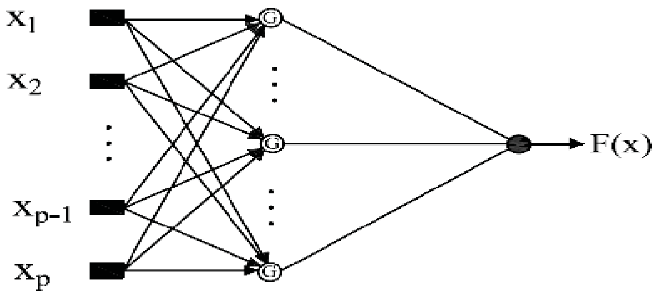

Fig. 1: Architecture of a radial basis function network.

The RBF network with m-dimensional real vector input and real output can be considered as a mapping function $F(x): R^n \rightarrow R$ .We examine a fully connected RBF network to approximate F(x) and use the normalized Gaussian function for neurons in a single hidden layer according to:

$$F(x) = \sum_{1}^{N} w_i \varphi (\|x - c_i\|)$$

where is the input vector of a sample record, N is the number of hidden neurons, are the weights to the output layer, is the basis function and is the center of the i-th basis function. is the Euclidean distance between x and the and w_0 is the bias weight with input $\varphi (\|x - c_i\|)$. The weights can be estimated using the matrix methods of linear least squares, because the approximating function is linear in the weights. The Gaussian function and thin-plate-spline function are two popular choices. Usually the Gaussian radial basis function is used, i.e. . We can use RBF networks to approximate any continuous function $f(x_i) = b_i$, i=1,…, c by fitting the values of the function at known points .

In the proposed method, the network has two inputs and two outputs. The initial stage entails the deployment of the wireless sensor network in the actual working environment and the collection of a "calibration" data set containing both the actual position data and the estimated position data resulting from WSN-based positioning algorithm for known points. Presented with the "calibration" set, RBF NN will be trained to decipher hidden relationships and complex patterns on the positioning errors of the wireless sensor network. Once trained, RBF NN will be used to recall the actual position of a mobile node when presented with a new positioning scenario. In order to achieve high accuracy, the RBF NN will be continuously updated by adding new training cases to the underlying calibration set. A major benefit of a neural network model is that prior knowledge of the noise distribution is not required. Noisy location measurements can be used directly to train the network with the actual coordinate locations. The resulting NN model is capable of characterizing the noise and compensating for it to obtain the accurate position. This differs from the Kalman filtering technique, which depends upon the knowledge of noise distribution to enhance localization accuracies (Shareef 2008).

5. System Implementation

To examine the feasibility and limitations of our system and to evaluate the performance of our system in an indoor environment, a dynamic error test using the prototype positioning system was performed in an underground parking lot at the University of Alberta. Construction sites are dynamic environments, which are exposed to movement of equipment, materials and laborers. Therefore, we intended to evaluate the proposed localization system's performance for tracking mobile resources that frequently travel from one location to another, such as human and material delivery systems; e.g., a mobile machine or an indoor crane. The objective of the dynamic error test was to evaluate the difference between the true known traveling path and the estimated path to find the level of accuracy of the system. An underground parking lot was selected for this purpose because it can simulate the challenges and complex characteristics posed by the construction environment. The building 1) was built with concrete and 2) has steel access doors, metallic cages, concrete columns and power cables located near the test area that may cause interference with the WSN communication system. In addition, heavy foot and vehicle traffic in this area can cause signal communication errors, because human bodies can absorb the signal, while metal obstacles tend to reflect a signal.

The experiment was conducted by deploying a number of nodes within the monitored area. Fig. 2 shows a sample distribution of nodes for the experiment and describes the test area layout with 18 receivers at fixed locations (marked as solid squares) and a remote node (marked as solid circle) which is set to move along a square-shaped path of 8×6 meters. Profile samples are marked as × every 2 meters whose pre-defined local locations are known. A path was determined and a tag was carried by a human along the path at less than a normal walking speed. In the data collection phase, the nodes exchange an enormous number of packets, passing their parameters including sender/receiver ID, transmitter parameters, serial number and RSS to the central node. The central node is connected via a USB dongle to a laptop, where all the data collected by the network is accumulated. During the data collection, some of the collected readings are saved in a profile database of the positioning system, while some others are stored as tracking data. The RF module of EMSPCC11 proposes several settings (Haque et al. 2009) of the packet bit rate, transmitted power level, and the channel number. The bit rate alternatives are 5 kbps, 10 kbps, 38 kpbs, and 200kbps. The transmission power can differ from -30 dBm to 10 dBm, and there are 256 different channels with 200 kHz spacing. All combinations are possible and, in principle, sensible. The experiments were carried out at power level 2 with 5kps transmission rate using channel 0.

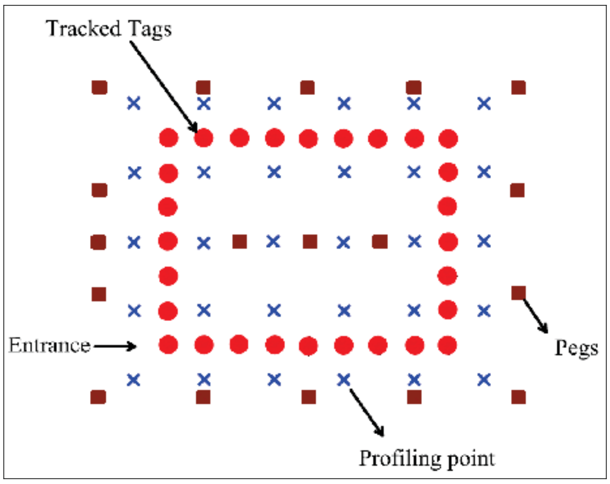

Fig. 2: Tag placement in the parking lot

The position of the tag was measured every 1 meter. The localization error vector is assumed to be the Euclidean vector connecting the actual and estimated location in Euclidean space. In this manner, the localization error magnitude is the Euclidean distance between the two points. The average errors' magnitudes for different K (number of best-matched samples) were investigated to find the best K (Fig. 3). K=7 was selected as it results in the smallest average localization error. The standard deviation of the errors was determined to be from 0.42 to 0.76 meters, demonstrating that the greater the number of K, the smaller the standard deviation.

The results from the experiment (Fig. 3.) indicated that the system is able to locate the tracked tag with an accuracy of 1.11m only by using WSN-based positioning architecture. Considering the application requirements, a localization of less than 2m is acceptable to locate mobile assets in construction sites. Therefore, these findings may attract interest and provide motivation for possible deployment in industrial applications, because an average error of 1 meter could provide an allowable resolution of accuracy for many large-scale construction sites. Fig. 4 shows the true path and the estimated path using WSN. The observed path agrees nearly with the true path with an acceptable level of accuracy. However, an added caveat is that the introduction of significantly bigger (or many) obstacles is bound to downgrade the localization performance. In an extreme situation, the wireless signals we use can be drastically attenuated. Therefore, for many applications in the construction area, there is a need for a robust positioning system with higher localization accuracy. In the following section, an error enhancement approach utilizing RBF NN is described and the results are discussed.

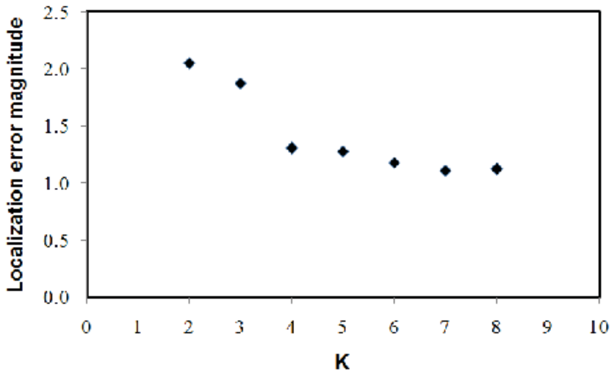

Fig.3: Average localization errors for different K

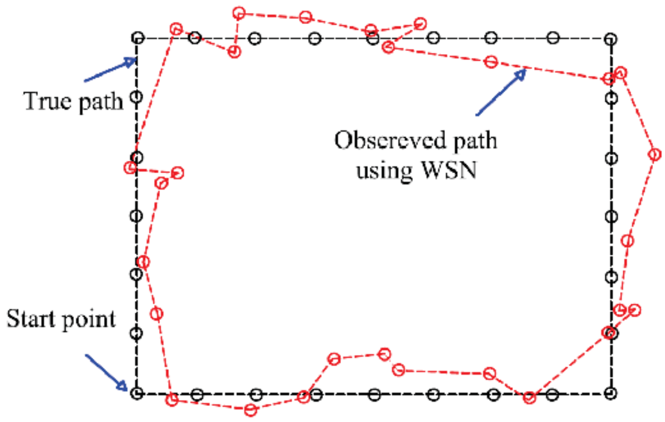

Fig. 4: true traveling path versus Observed path by WSN

In the calibration phase, we collected samples of estimated locations by WSN every 2 meters on the desired path. The locations are measured in two dimensional coordinates and are stored in a database called “Location map”. Later, this location map was used to provide training samples for the RBF NN model. The training phase was used to train different neural networks and analyze their comparative performance. The Radio Map generated in the calibration phase was used to train RBF NN.

After the training phase, live data from the environment needed to be tested with trained neural networks. In the estimation phase, the WSN-based estimated location captured on the mobile device was presented to the input layer of neural network. Thus, RBF NN was used to recall the actual position of the mobile node when presented with estimated positions of the rest of the points on the path. Results are presented as estimation error in terms of meters. We employed Euclidean distance between estimated and actual location to represent error. The results demonstrate that the average localization error for tested data is reduced from 1.10 m and standard deviation of 0.92m to 0.57 m and 0.55 m, respectively, for 14 positions. The robust nature of this localization technique in a dynamic environment thus implies its potential for deployment in real dynamic construction sites.

6 Conclusion and future direction

The presented study introduces a new framework for automating the identification and localization of construction resources in industrial projects. In this approach a methodology associated with wireless sensor networks (WSN) was used to facilitate an indoor data collection process. The localization approach utilizes a database of signal strength readings from tags located at known positions within the monitored area obtained during a profiling phase. Subsequently, a best matched set of profile points is selected to determine the location of closest reference points to a tracked tag emitting an RF signal from an unknown place and then average coordinates of those points will be an approximate location of the tracked sender. A Redial Basis Function neural network was employed to reduce the localization errors, and the experimental results indicated a large performance improvement in localization with only limited training data. An indoor experiment assessed the feasibility of this automated methodology in a realistic construction scenario. The localization approach resulted in good estimated locations that could facilitate the efficient localization of the tagged components. Employing a WSN based positioning system as the infrastructure associated with RBF NN as an error filter for indoor location awareness is a prudent choice, due to its low cost and pervasive coverage. As a result, it is believed that the WSN based positioning methodology being proposed will provide a practical solution for construction asset tracking with better accuracy and advanced networking capability, potentially enabling resource or component tracking and visualization in augmented reality (AR) or mixed reality (MR).

One of our goals for future is to investigate the placement of the pegs in the monitored area in order to identify a peg layout design that features a smaller set of fixed points (pegs) while still resulting in good localization performance in a particular experimental setting. Moreover, the method being proposed will be refined into a self-adaptive, self-calibrating, real time positioning solution based on frequent, dynamic RSS re-profiling. Although we observed from the testing the patterns of the changes in the RSS map are insignificant with one “car” obstruction introduced to the test setting, the proposed methodology will be feasible and computationally efficient to re-profile and recalibrate the positioning solution on a preset time frequency. As such, the added profiling points in the testing area can be removed; instead, each peg node fixed on a known location can be taken as a profiling reference point. The RSS between one peg node and other pegs in the system will be collected and mapped onto the location coordinates of the peg from time to time. This helps address the dynamic changes on a practical construction site.

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DEVELOPMENT OF PRE- AND POST-PROCESSING SYSTEMS BASED ON VIRTUAL REALITY FOR 3-D FLOW SIMULATIONS

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ABSTRACT: *This paper presents interactive pre- and post processing systems based on virtual reality technology for three dimensional finite element flow simulations. The mesh modification system is developed for the pre-processing system and the flow visualization system is developed for the post-processing system. The CAVE library and OpenGL are employed for the development of the systems. Users can modify the mesh quality and can visualize the numerical results interactively by using the controller in VR space. The present systems are applied to the large scale wind flow simulation in urban area and are shown to be useful systems to realize the high quality computing.*

KEYWORDS: *three dimensional flow simulation, mesh modification, flow visualization, high quality computing, CAVE*

1. Introduction

The three dimensional flow simulations are becoming more powerful and popular tool for planning and design of various construction projects in accordance with the development of hard- and software of computers. However, the following problems are pointed out in pre- and post-process for practical computations as: 1) it is difficult to check and modify the quality of mesh for the complicated spatial domain, 2) it is difficult to understand the three dimensional flow field accurately, especially to the depth direction, since the computational results normally express on the 2D screen or display.

This paper presents interactive pre- and post processing systems based on the virtual reality technology for large scale three dimensional flow simulations in order to overcome above problems.

The mesh modification system for three dimensional flow simulation based on unstructured grid is developed for the pre-processing system. The present authors have been presented a prototype system for the mesh modification (Kashiyama et al. 2010). Users can check the details of three dimensional mesh structures and can modify the shape of mesh idealization in VR space interactively by using the controller.

However, as the node relocation method was only employed for the mesh modification method, the improvement of mesh quality was not sufficient. In order to improve the mesh quality sufficiently, the mesh refinement method is introduced as a new mesh modification method in this paper. For the finite element mesh, the four nodes linear tetrahedral element is employed. Users can select the modification method from the menu which is displayed in the VR space. Users can change the nodal position of the bad quality element in case of the node relocation method, and can refine the bad quality element in case of the mesh refinement method.

On the other hand, the flow visualization system based on unstructured grid is developed for the post-processing system. The present authors have been presented a system for the flow visualization for vector and scalar field (Yamazaki et al. 2010). Users can select the visualization method from the menu displayed in the VR space by using a controller. The concept of the system is similar to the VFIVE (Kageyama et al., 2000, Ohno and Kageyama, 2007) based on structured mesh. As the visualization based on unstructured grid is time consuming comparing with that based on structured grid, the reduction of the computational time have been realized by the development of the fast algorithm for visualization. However, the system is not sufficient for the kind of visualization methods to show the computed vector and scalar data quantitatively. In order to overcome the problem, a graph drawing function is developed as a new visualization method.

The present systems are applied to wind flow simulation in urban area and are shown to be useful tools to realize the high quality computing for large scale three-dimensional flow simulations.

2. VR Environments

The present systems are designed for the use of virtual reality system based on IPT (Immersive Projection Technology) such as CAVE (Cruz-Neira et al, 1993, Wegman and Symanzik, 2002). The stereoscopic view is realized in VR space by creating the images that corresponds to binocular retinal images. FIG. 1 shows the exterior view of the VR system "Holostage" of Chuo University. FIG. 2 shows the hardware configuration of the system, which consists of a PC cluster (one master-PC and four-slave-PC), three projectors, three large screens and a position tracking system. The master PC manages the action of whole system, the slave PCs perform the position tracking of user's glasses and controller, and the slaves PCs 1-3 perform the computation for visualization and display the visualized results by CG image for each screen. The stereoscopic image from the arbitrary viewpoint of observer is displayed in VR space by the position tracking system. The details of the VR system are described in the reference (Takada and Kashiyama, 2008). FIG. 3 shows the tracker device VICON (FIG. 3(a)) which tracks the position of markers fitted to the liquid crystal shutter glasses (FIG.. 3(b)) and the controller (FIG. 3(c)), the white small ball in FIG. 3(b) and (c) denote the marker. The six VICONs are located on the top of front and side screens.

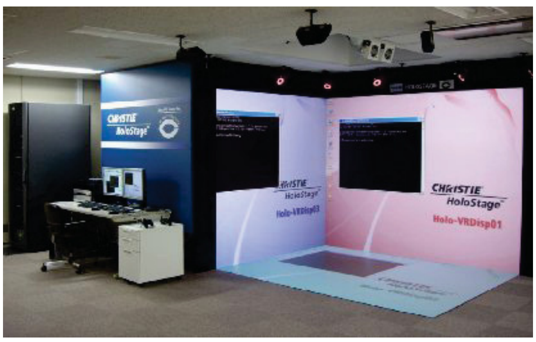


Fig. 1: VR system "HoloStage"

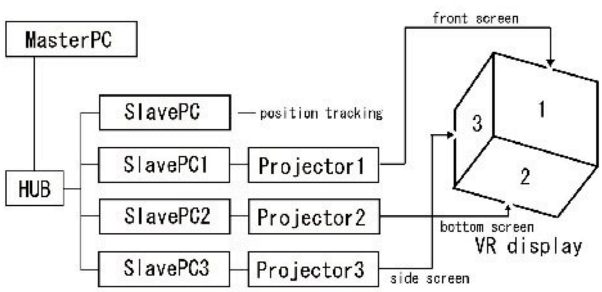


Fig. 2: Hardware configuration

FIG3: tracker device (a), liquid crystal shutter glasses (b) and controller (c)

3. Pre- and Post-Processing Systems

3.1 Flow Chart

FIG. 4 shows the flow chart of the present system. Users can check the details of three dimensional mesh structures and modify the shape of mesh interactively in VR space by the pre-processing system. On the other hand, users can investigate the three dimensional flow phenomena precisely by the post-processing system. The present systems are developed by the VR programming languages, Open GL and CAVE library. For the finite element mesh, the four nodes linear tetrahedral element is employed.

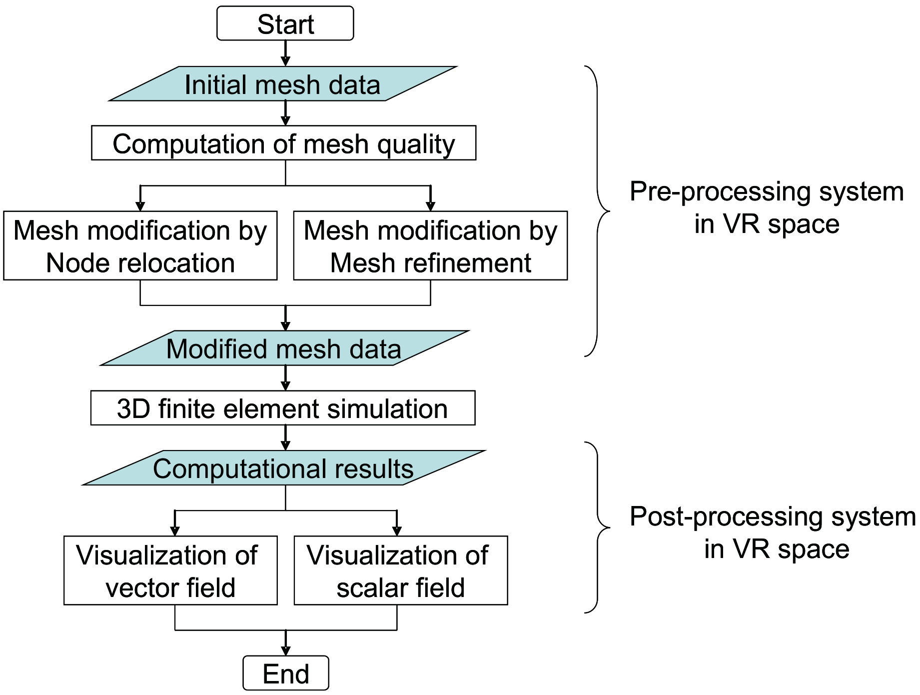


Fig. 4: Flow chart

3.2 Pre Processing System

Users can investigate the details of mesh structure and to improve the mesh quality by the mesh modification method interactively in VR space. The modification method by mesh refinement is added as a new modification method to the conventional system (Kashiyama et al., 2010).

3.2.1 Input data and mesh quality

The mesh data is prepared for the input data for pre-processing system. The four nodes tetrahedral element is employed for the finite element. The Delaunay triangulation method (Takada and Kashiyama, 2008, Kashiyama et al, 2009). is employed for the mesh generator.

The mesh quality can be evaluated by the following equation (Freitag and Knupp, 2002)

$$Q_m = \frac{\left(\sum_{i=1}^{6} L_i^2 \right)^{\frac{3}{2}}}{8.4796V} \tag{1}$$

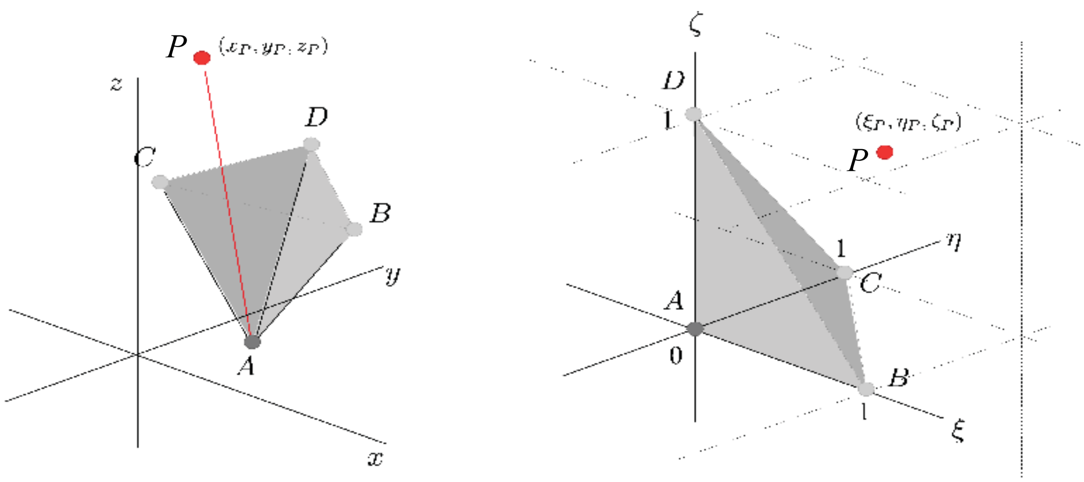
where L_i denotes the length of the edge of the element, V is the volume of the element. The mesh quality is to be 1 if the element is to be a regular tetrahedron and the value is to be big value if the element becomes a bent element. In this system, the elements which exceed the setting value for mesh quality are displayed by the red color in VR space.

3.2.2 Modification by mesh refinement method

In the modification by mesh refinement, the elements which exceed the setting value for mesh quality are refined. Users can specify the element by using the controller. If users move the tip of beam generated from the controller to the inside of the element and click the button, then the element can be specified. In order to investigate the judgment that the element includes the tip of beam or not, the mapping method using a generalized coordinate system is employed. FIG. 5 shows the mapping from the physical domain to the mapped domain based on the generalized coordinate system, where the point P denotes the position of the tip of beam. If the coordinate of the point P in the generalized coordinate (ξ_P, η_P, ζ_P) is satisfied the following condition, the point P is included in the element A-B-C-D.

$$(0 \le \xi_P \le 1) \cap (0 \le \eta_P \le 1) \cap (0 \le \zeta_P \le 1) \cap (\xi_P + \eta_P + \zeta_P \le 1) \tag{2}$$

Fig. 6 shows the pattern of refinement. The new node is generated at the centroid of the element and the element is subdivided into four smaller elements.



(a) Physical coordinate *(b) Generalized coordinate*

Fig. 5: Search of the element using the generalized coordinate

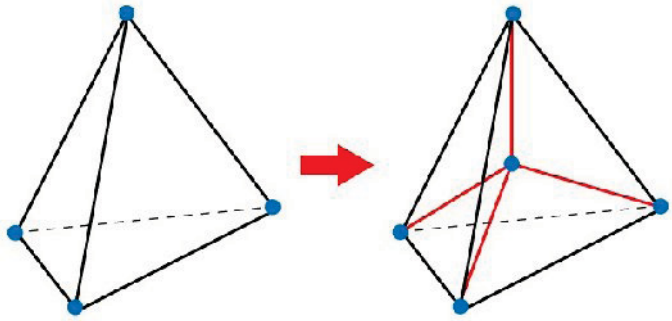


Fig. 6: Pattern of the refinement

3.2.3 Modification by node relocation method

In the pre-processing system, the modification method by node relocation is also available in order to improve the mesh quality (Kashiyama et al., 2010). However, it is possible to violate the geometrical shape by the node relocation. In order to avoid this problem, the node movement condition must be introduced for the nodes on the boundary. The condition is prepared by the geographical information, which is obtained by the mesh data. The nodes of the mesh can be classified into four kinds, nodes at apex point, nodes on the edge-line of the boundary, nodes on the surface of the boundary and nodes in the computational domain. FIG. 7 shows the example for the mesh around a cubic structure. The nodes at the apex (gray nodes in Fig. 7) are assumed to be fixed point. The nodes on the edge-line of the structure (red nodes) can move on the edge-line only. The nodes on the surface of the structure (green nodes) can move on the surface of the boundary only. The nodes in the computational domain (blue nodes) can move to any direction. In this system, if the element violates the geometrical shape by the node relocation, the element is displayed by the green color in VR space.

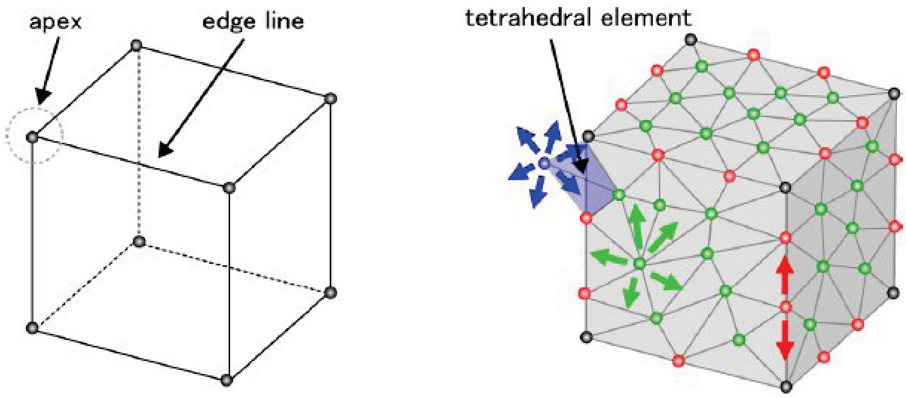


Fig. 7: Node movement condition

3.3 Post-processing System

Users can investigate the details of flow structure interactively in VR space. The graph function is added to the conventional system (Yamazaki et al., 2010) as a new visualization method.

3.3.1 Input data

The input data for the post processing system is as follows; unstructured mesh data based on linear tetrahedron element, the data for computational results for vector data (velocity) and scalar data (pressure and density (in case of compressible flow)) at nodes of the tetrahedron element. In case of unsteady simulation, the data for computational results are prepared for every time step.

3.3.2 Selection of visualization method

The present system provides the following visualization methods in the VR space; isosurface, contour lines, color slice, particle tracing, field line and so on. The major visualization methods of present system are listed in Table 1. The observer can select the visualization method from the menu displayed in the VR space by using a controller (see Fig. 8).

Table 1: Major visualization methods of present system

For Vector data	For Scalar data
Field Lines	*Isosurface*
Particle Tracer	*Local Slicer*
Local Arrows	*Ortho Slicer*
Spotlighted Particle	*Volume Rendering*
Strem Surface	*Probe&Graph*
Line Advector	
Probe&Graph	

Fig. 8: Menu of visualization method (for velocity field)

3.3.3 Calculation for visualization method

For the visualization using unstructured grid, it is very important to find vector and scalar quantities at the designated point quickly. To do this, it is necessary to find the element where the designated point is included quickly. To do this, the search algorithm using bucket method and generalized coordinate system has been developed. The details are described in the reference (Yamazaki et al., 2010).

Once, the element that includes the designated point is searched, the vector value and scalar value at the designated point is interpolated by the value of the element node in the generalized coordinate system as follows (see Fig.9).

$$q(\xi_P,\eta_P,\zeta_P) = q_A + \left(\frac{q_B - q_A}{\Delta\xi}\right)(\xi_P - \xi_A) + \left(\frac{q_C - q_A}{\Delta\eta}\right)(\eta_P - \eta_A) + \left(\frac{q_D - q_A}{\Delta\zeta}\right)(\zeta_P - \zeta_A) \qquad (3)$$

where, q_A, q_B, q_C, q_D denote the vector and scalar value at the element node.

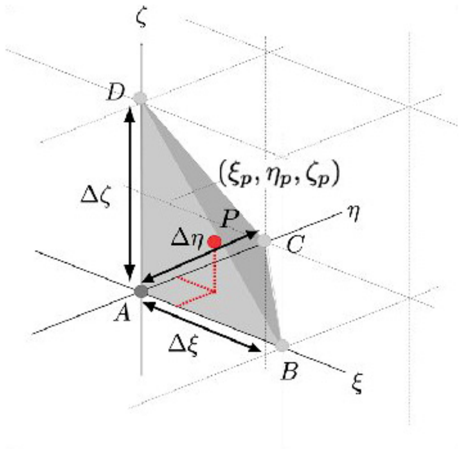


Fig. 9: Interpolation of vector and scalar value

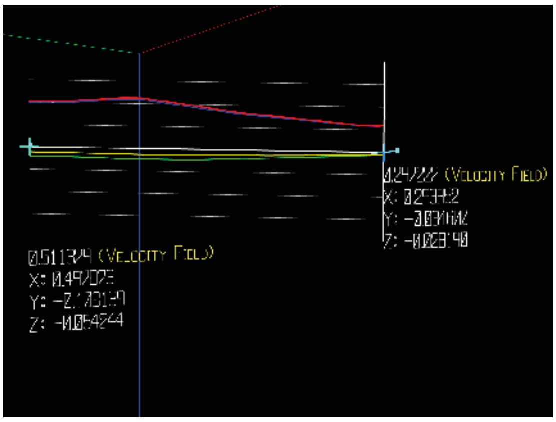


Fig. 10: Graph function for vector and scalar values

In this paper, a graph function is developed as a new visualization tool "Probe&Graph". Users can draw the line graph for vector and scalar values between two destination points. The length between two destination points are subdivided into 100 and the vector and scalar values are interpolated at the divided points using nodal values. FIG. 10 shows the example for the vector values. In this figure, the values for X, Y, Z denote the vector values at the destination (edge) points.

4. Application Example

The present system is applied to the large scale simulation of wind flow in urban area. FIG. 11 shows the aerial-photo (Google) of the studied area, Nihon-bashi, Tokyo, and the circle area denotes the modeling area. For the modeling method, the method using GIS/CAD data is employed for creating the shape model and the Delaunay method is employed for the mesh generation based on unstructured grid (Takada and Kashiyama, 2008, Kashiyama et al, 2009). For the data for buildings, the GIS data (Mapple 2500) which is developed by the aerial-photo and survey is employed. For the land elevation data, the digital elevation map issued by the Japanese geographical survey institute, which is developed by the aerial-laser survey, is employed.

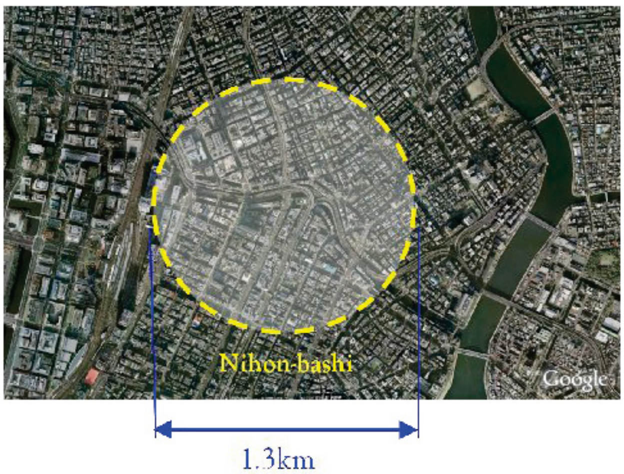


Fig. 11: Studied area, Nihon-bashi, Tokyo

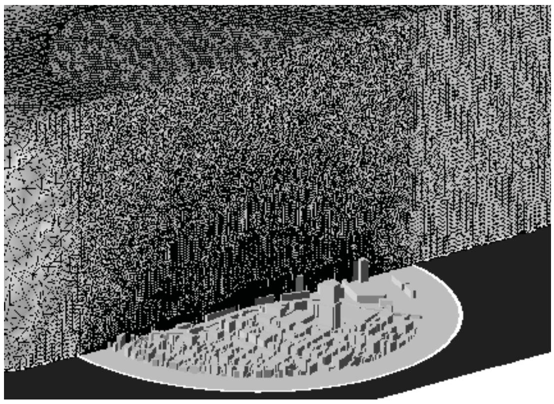


Fig. 12: Mesh idealization for wind flow simulation

FIG. 12 shows the finite element mesh idealization based on the four nodes linear tetrahedral element. The fine mesh is employed near the ground and buildings. The total number of nodes and elements are 2,458,388 and 14,115,104 respectively. From this figure, it can be seen that; 1) it is difficult to check the quality of the shape model and mesh idealization for the complicated spatial domain by the visualization based on two dimensional expressions using the perspective drawing. 2) It is difficult to modify the mesh to improve numerical accuracy and stability.

In order to overcome both problems, the present pre- and post- processing systems are applied to the box region in FIG. 13. FIG. 14 shows the scene the user modifies the mesh idealization manually using the mesh modification by mesh refinement method. From this figure, it can be seen that the element selected (green element) by user is subdivided into four smaller elements.

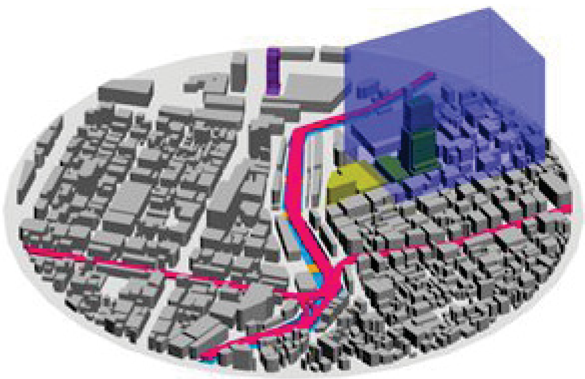


Fig. 13: Application area, Nihon-bashi, Tokyo

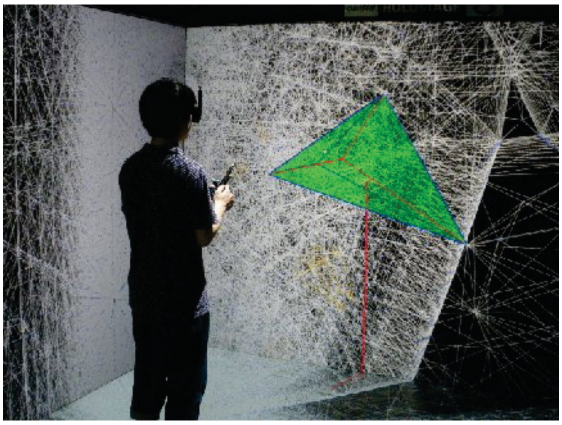


Fig. 14: Mesh modification by mesh refinement method

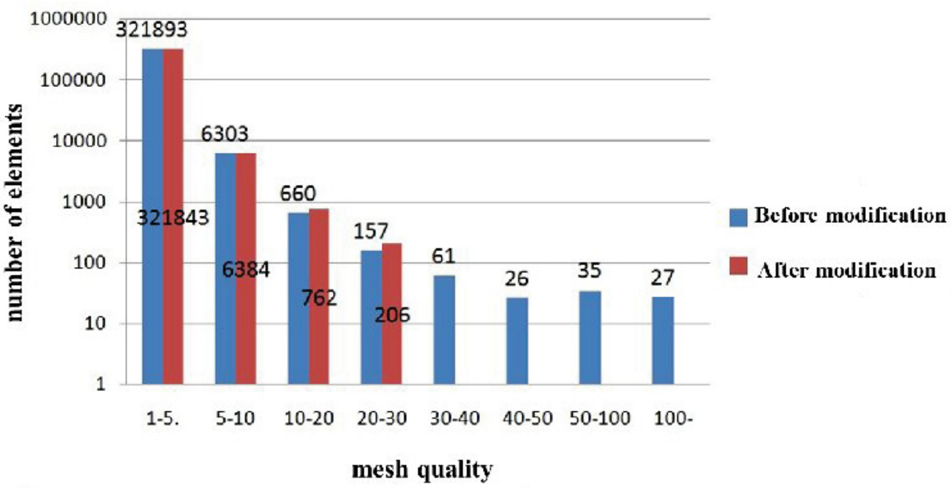


Fig. 15: Distribution of mesh quality

FIG.15 shows the comparison of the distribution of mesh quality before and after the mesh modification by mesh refinement and node relocation. In this case, the bad shaped elements which exceed the mesh quality values “30” are modified by the present method. From the figure, it can be seen that the bad shaped elements which exceed the mesh quality values are erased perfectly. The operation time to correct the bad shaped mesh (total number of elements are 149) was about 30 min.

The stabilized parallel finite element method is employed for the wind simulation (Kashiyama et al., 2005). FIG. 16 shows the computational domain and boundary conditions. The incident wave angle is changeable by the rotation of the turn table. For the governing equations, the incompressible Navier-Stokes equations with LES (Large Eddy Simulation) are employed. FIG. 17 shows the domain decomposition for parallel computation based on MPI.

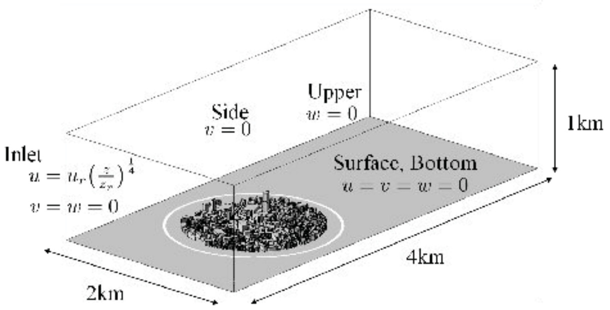


Fig. 16: Computational domain

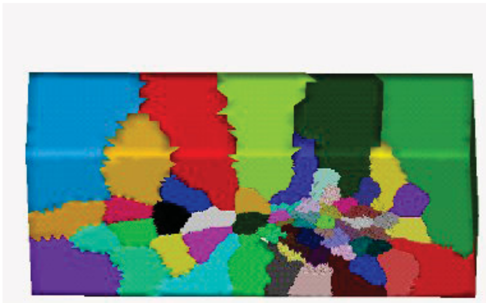


Fig. 17: Domain decomposition for 64 subdomain

FIG. 18 shows the comparison of computed streamline by the change of incident wind direction (0 degree and 40 degree in counter clock-wise) using commercial visualization software AVS. From this figure, we can understand the flow phenomena qualitatively, but it is difficult to understand the flow phenomena quantitatively. Therefore, the present interactive post processing system is applied to this problem.

FIG. 19 shows the scene that the observer uses several visualization methods “Field line” (which shows streamline), “Local Arrows” (which shows velocity vector) and “Probe&Graph” (which show vector and scalar values with graph function), to investigate the three dimensional vortex occurred behind the building. It can be seen that the present visualization system based on unstructured grid is very useful for the three-dimensional flow problems with complicated geometry.

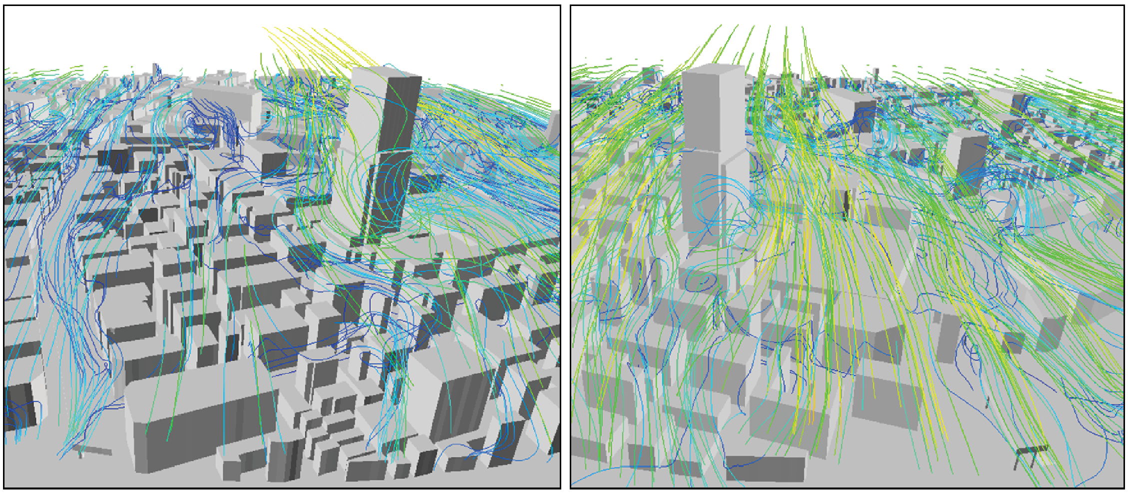


Fig. 18: Computed streamlines: 0 degree (left), 40 degree (right)

5. Conclusions

The interactive pre- and post-processing systems based on the virtual reality technology for three dimensional flow simulations have been developed. The present systems are applied to a large scale wind flow problem in urban area. The following conclusions can be obtained.

- Users can improve the numerical accuracy and stability by using the mesh modification system based on node relocation and mesh refinement.
- ・Users can understand the three dimensional flow phenomena quantitatively by using the flow visualization system based on unstructured grid.

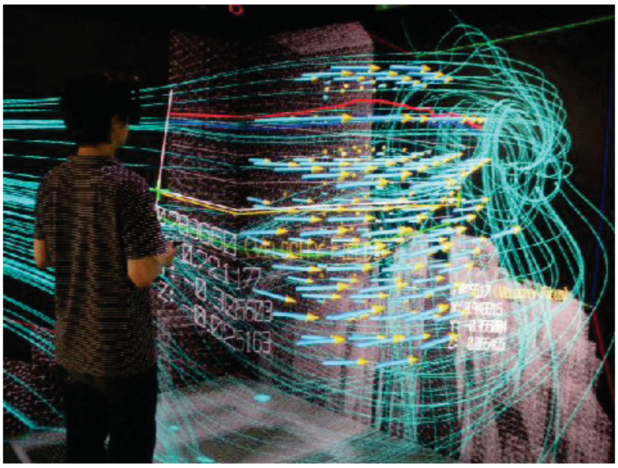


Fig. 19: Visualization by using several methods

From the results obtained in this paper, it can be concluded that the present systems provide useful tools to realize the high quality computing for large scale three-dimensional flow simulations.

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REGISTRATION OF AUGMENTED REALITY USING FOUR-MARKER METHOD FOR DESIGN AND CONSTRUCTION

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ABSTRACT: *One of the most critical issues in Augmented Reality (AR), when it is used outdoors in a large scale rather than on a desktop, is the accuracy of registration of the video camera in the real world. As the error depends on the size of the marker when using ARToolkit, a large marker should be used, which is cumbersome. In our research, the four-marker method was developed in order to utilize AR outdoors in a large scale for design, construction and maintenance of Architecture, Engineering, and Construction (AEC) industry. In order to evaluate and compare the errors of the conventional single marker method and the four-marker method, a series of experiments were performed in this research. The result was that the four-marker method showed much better performance compared with the single marker method. And images of virtual objects of AR in the four-maker method case were stable even when the distance between the video camera and the set of four markers is relatively large, whereas the single marker method case showed fluctuating images on the monitor. Then, we executed regression analysis and obtained a dimensionless equations for the given condition so that we could estimate errors for the future usage easily.*

KEYWORDS: *Augmented Reality, Registration Error, Outdoor, Four-Marker Method, Regression Analysis, Large Structures.*

1. Introduction

Augmented Reality (AR), which can superimpose real-time virtual computer graphics (CG) objects in a real video image, is deemed as a prospective technology to be used for various purposes in Architecture, Engineering and Construction (AEC). Especially, AR is useful when it is used to superimpose a virtual structure to be constructed in the near future for planning, consensus building, construction management, and maintenance on site. One of the most critical issues in AR, when it is used outdoors in a large scale rather than on a desktop, is the accuracy of registration of the video camera in the real world. There are three methods available at present. First is an image-based method in which an image of a special marker is used for locating the position and direction of the video camera in terms of the marker's location. This method is very popular because a free open source library, ARToolKit (Kato et al. 1999), is available. The second is a sensor-based method in which Real Time Kinematic Global Positioning System (RTK-GPS) and gyroscopes are used for obtaining location and direction of the camera (Feiner et al., 1997). Although this method is very accurate, it is heavy and expensive. Recently, smart phones that have simple GPS and electronic compass functions can be used for AR applications such as Sekai Camera and Wikitude. However, the registration accuracy is not high and the monitor size is not large enough for professional AEC applications yet. The third is a feature point-based method where feature points extracted from video images are matched with points of existing structures of which locations are already registered in the system (Jiang et al., 2001). This method is not mature enough and the research is still on-going.

In ARToolKit, if a marker, which is represented as a square and a character inside, is seen in a video camera image, the edge lengths and the shape of the rectangle of the marker on the screen are measured and the user's location and viewing direction are computed. However, since this method relies on the image of a single marker on the video screen, accuracy may not be always satisfactory, especially when the application is in large scale structures in civil and building engineering. Very large markers had to be used for outdoor purposes in the past (Pasman et al., 2004; Yabuki et al., 2009; Yabuki et al., 2011). Therefore, we developed the four-marker method (Ota, Yabuki et al., 2010). In this method, first, four markers are set up in a form of one square and treated as a single large maker. Next, the four markers are recognized individually by ARToolKit, and the central coordinate of the respective marker is acquired. Each central coordinate is assumed to be a vertex coordinate of one large marker hypothetically. Position and inclination of the camera is presumed by distance between the markers and shape of the hypothetical large marker. In this way, precision of recognition does not rely on the size of the marker but on the distance between markers. The experiment of this method showed better performance compared to the single marker method. However, the experiment was done only for the case where four markers were pasted on the wall of a building, which is equal to the virtual object. That is the distance between the four markers and the object which the virtual object itself should be overlapped is zero. Apparently, more experiment cases where the distance is over zero, for example, 100m, 500m, etc. must have been executed. Therefore, the objective of this research is to execute such experiments and evaluate errors, comparing the conventional one-marker method and the four-marker method.

2. ARToolkit

Since ARToolKit was used in this research, the operation of ARToolKit is described in this section. The operating principle can be divided into 1) detection of markers, 2) estimation of 3D position of markers, 3) rendering of virtual objects.

First, ARToolKit executes binary image processing of the input image from a video camera by the predetermined threshold value. Each pixel usually has an RGB values from 0 to 255 and the average of each color value becomes brightness of the pixel. Binarization, i.e., classifying all pixels as on or off (white or black), enables detection of target objects from given images easily. The threshold value must be specified in ARToolKit and its default value is 100.

Next, connected pixels are classified as sets of connected areas by binarization, and the area and circumscribed rectangle of each group are computed. Based on the computed values, very large or very small groups are excluded from the candidate list of the marker. For the remained connected areas, contour (outline) tracing is performed and the coordinates of the pixels of the contours are obtained. Then, the broken line approximation is executed for the contours, and several connected areas that are approximated by a quadrangle are selected as candidates of the marker. Coordinates of each vertex of the quadrangle are obtained and the center of the quadrangle, which will become the origin of the marker if selected, is computed. Then, the connected area inside the quadrangle is compared with the prescribed pattern of the marker by template matching, and the candidate with the pattern of the highest estimated value is identified as the marker. The pattern of the marker can be defined by the user, but the figure must correctly identified even if the pattern is rotated.

By using coordinates of the four vertexes of the marker on the screen coordinate system in the marker detection process, transformation matrix from the marker coordinate system to the camera coordinate system is estimated. The relative position relationship between the camera and the marker can be evaluated using the transformation matrix.

Predetermined 3D object which is linked to the marker can be rendered using functions of the Open Graphics Library (OpenGL). Since the size of the marker has been measured, the unit of the length in the OpenGL can be matched to the length unit in the real world.

3. Four-Marker Method

This section describes the four-marker method, which was developed for the purpose of design, construction, and operation & maintenance (O&M) in AEC. In this method, first, as the size of each marker depends on the distance between the video camera and the set of the markers and the resolution of the camera, pre-experiment should be performed. If the marker size is 400mm x 400mm, the distance between the marker and the video camera is up to 14m.

Next, markers are to be installed so that the origin of each marker, i.e., the centre of the marker, is located on the vertex of a large virtual square. And the distance between markers, i.e., the length of the edge of the square is measured. Since the distance between the adjacent markers will be the base for the location and size of the virtual object linked to the markers, the value of the distance is very important. The larger the value of the distant, the better accuracy would be obtained. However, all four markers must be in the view of the camera simultaneously.

Then, four markers are identified using the function of marker detection of the ARToolkit from the input video image. If the marker cannot be detected properly, the threshold value of image binarization should be changed to fit the environment. The coordinates of the origin of each marker are obtained and saved in memory. Then, the four origins are transformed to the vertexes of a virtual large square marker, and estimation of position of the virtual marker is executed using ARToolkit. Then, the positioning of the virtual object represented as a virtual object can be done accurately based on the hypothetical large square maker composed of the four small markers. By this method, registration of virtual AEC structures in the real video image can be done more accurately than the conventional single marker method.

We implemented this method, using Open source Computer Vision (OpenCV) library, ARToolkit, Microsoft Visual C++ 2008 Express Edition. As for hardware, we employed a laptop PC of Sony PCG-51111N with Intel Core i7 CPU M640 (2.80 GHz), 4.00GB RAM, a monitor of 1366 x 768 resolution, and Operating System of Microsoft Windows 7 Professional. As a web camera, we used Logicool Qcam Pro for Notebooks with 1600 x 1200 resolution. Then, four markers of 400mm x 400mm were made as shown in Figure 1. The length of the edge of the hypothetical square of four markers was 1800mm.

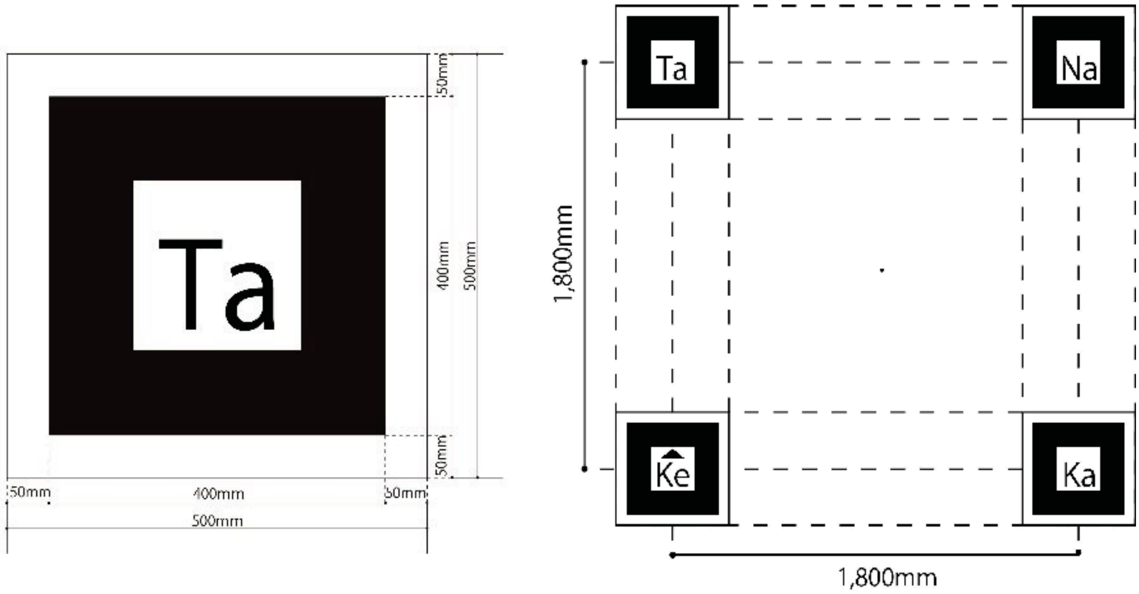

Fig. 1: Drawing of a marker and a set of four markers.

4. Experiment and Result

4.1 Method of experiment

In the experiment, three parameters, i.e., the angle *a* between the normal direction of the marker and the direction of the video camera, the distance *d* between the video camera and the set of the markers, and the distance *k* between the set of the markers and the building to be superimposed. As for the angle *a*, it is well known that the error is small if the angle ranges from 15 degrees to 60 degrees. Thus, we set the angle 20 degrees. As for the distance *d*, we had three cases, i.e., 5m, 8m, and 11m for comparison. Then, we selected four buildings so that the distance *k* has four cases, i.e., 56m, 123m, 250m, and 453m, as shown in Figure 2. For each building, a 3D frame representing the edges and vertices, which are the evaluation points, of the building was made using a 3D CAD software package and was registered precisely corresponding to the four markers. Figure 3 shows each case setting. The error was measured by counting the pixels of the gap between the vertex of the frame and the corresponding angle of the building image after capturing the video image in the memory (Figure 4). Then, the error (pixel) was converted to the actual distance by multiplying the factor between the pixels and distance. For each case, 10 images were captured because video images often fluctuate in the single-marker method, and the average error was computed.

Fig. 2: Experiment settings of distances k and d and angle of the video camera to the marker.

Fig. 3 (a): The building of which distance to the set of the markers (k) is 56m and its measuring points.

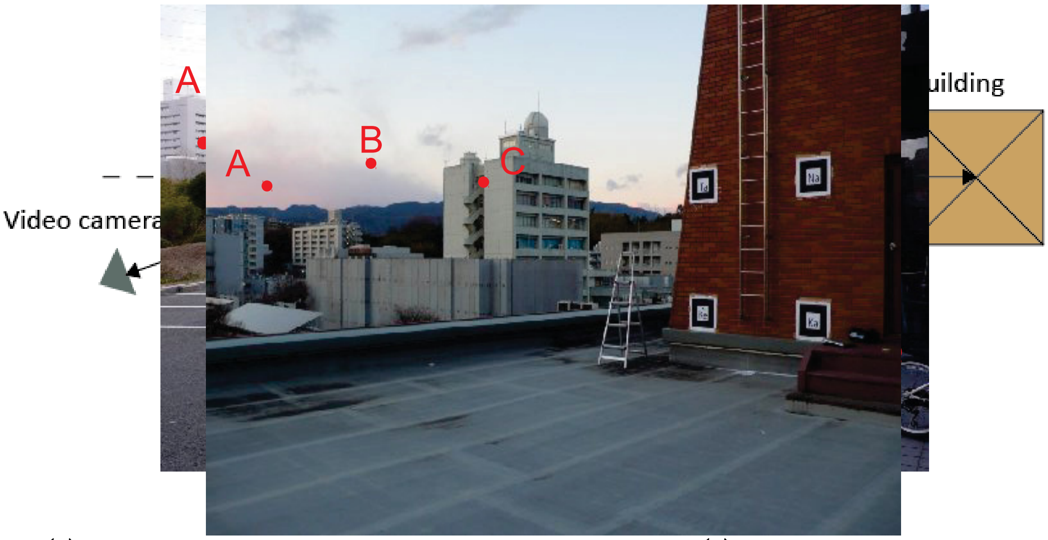

Fig. 3 (b): The building of which distance to the set of the markers (k) is 123m and its measuring points.

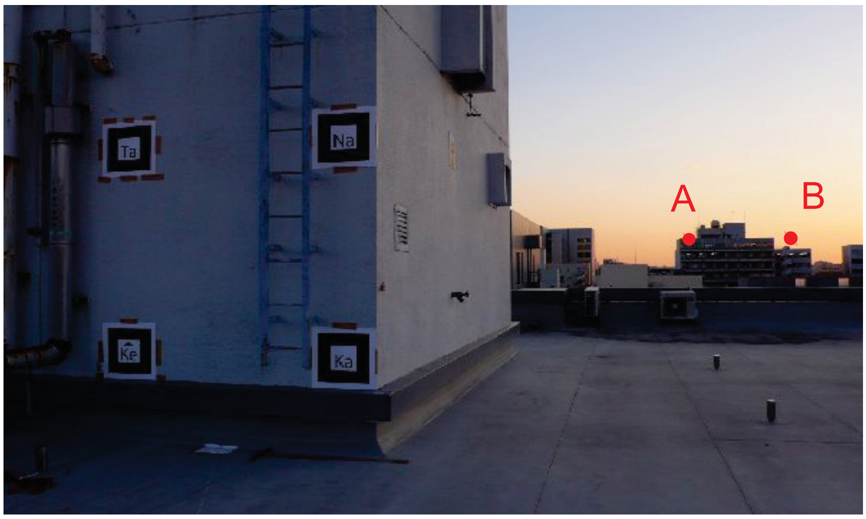

Fig. 3 (c): The building of which distance to the set of the markers (k) is 250m and its measuring points.

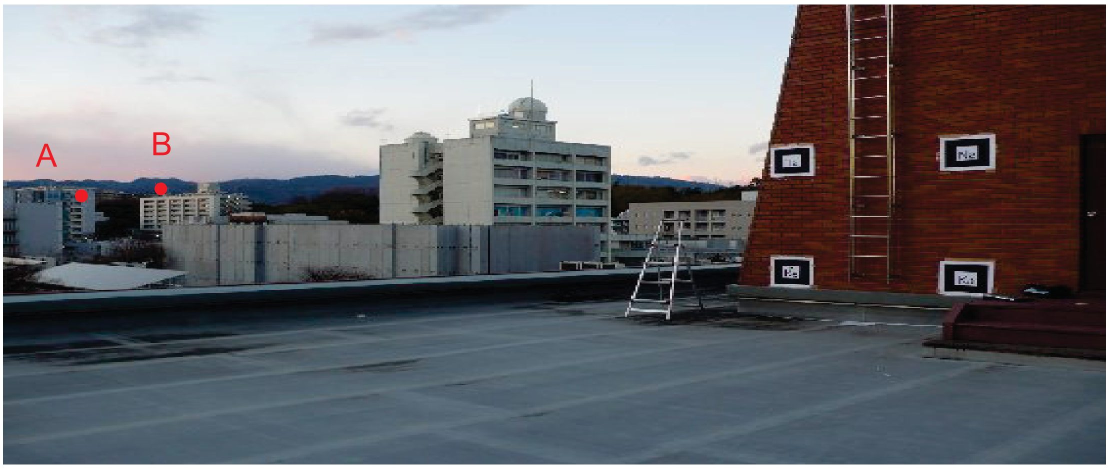

Fig. 3 (d): The building of which distance to the set of the markers (k) is 453m and its measuring points.

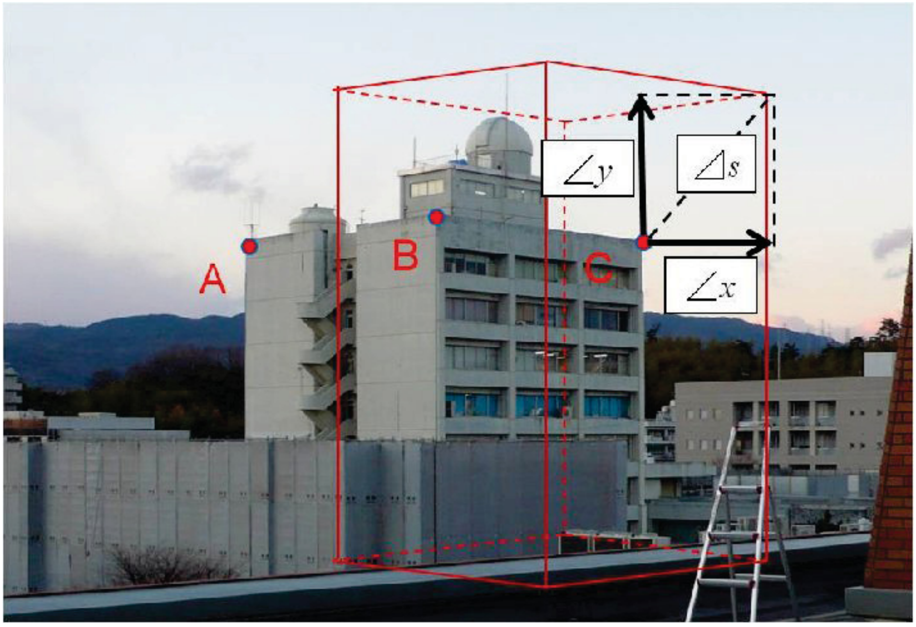

Fig. 4: The virtual object which represents the frame of the building and the method of error measurement.

4.2 Results of experiment

The relationship between the distance *k* and the average error for the single marker method and the four-marker method is shown in Figure 5 and Figure 6, respectively. Apparently, the four-marker method showed better performance in terms of the error. Furthermore, images of virtual objects of AR were stable even when the distance between the video camera and the set of four markers is relatively large in the four-maker method case, whereas the single marker method case showed fluctuating images on the monitor.

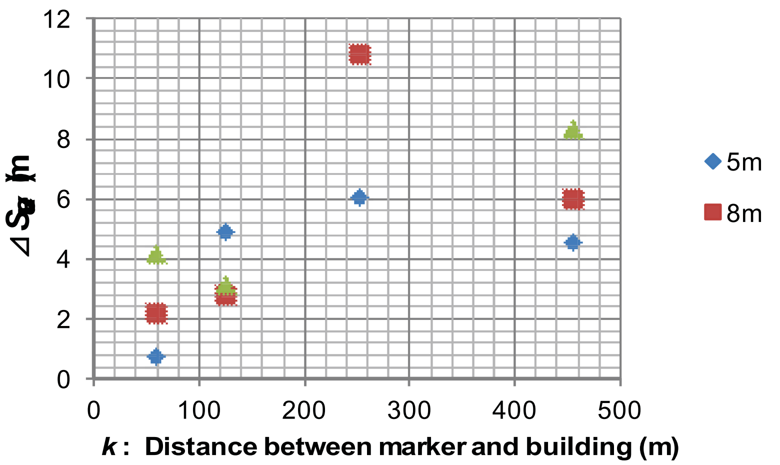

Fig. 5: Relationship between the distance k and the average error for the single marker method.

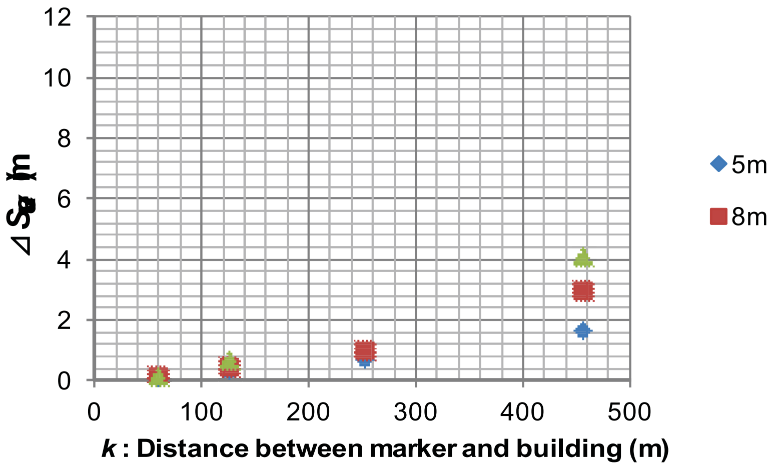

Fig. 6: Relationship between the distance k and the average error for the four-marker method.

Then, we analyzed the result of the four-marker method to obtain an error estimation equation. Figure 7 shows the statistical analysis result between the distance *k* and average error *e*. In order to obtain more generalized relationship, we introduced a dimensionless value of *E* (= *e* / *d*). Figure 8 shows the relationship between *k* and *E*. By the regression analysis, we obtained the following equation:

$$E = 8.63 \times 10^{-4} k - 3.52 \times 10^{-2}$$

The correlation coefficient was 0.9739.

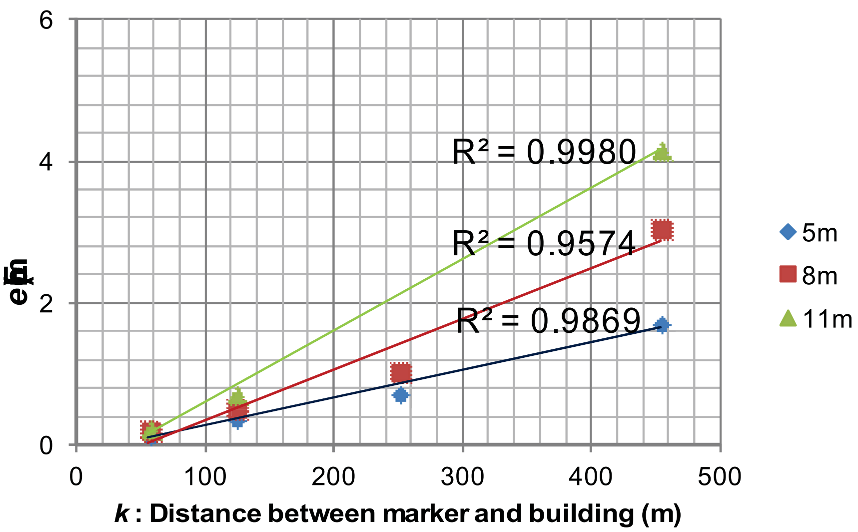

Fig. 7: Statistical analysis result between the distance k and average error e.

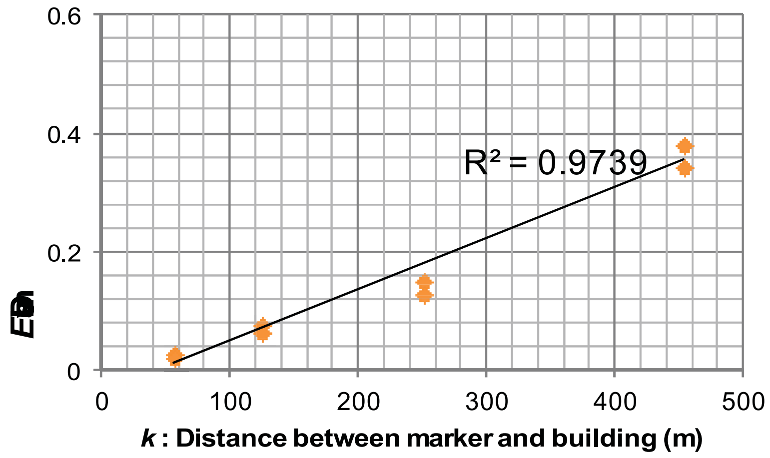

Fig. 8: Regression analysis result between relationship between k and dimensionless E.

To diminish the dimension and to adjust the coefficients, *k* was divided by 1,000m and dimensionless distance factor *K* (= *k* / 1000m) was introduced. We obtained the following equation:

$$E = 0.863K - 0.0352$$

This equation was derived directly from the experiment result by the regression analysis. By assuming that *E* should be zero if *K* is zero, we can erase the intercept coefficient and obtain the following equation:

$$E = 0.85K$$

Please note that this equation was based on the experiment condition that the size of the hypothetical large marker size was 1,800mm.

5. Conclusion

In our research, the four-marker method was developed in order to utilize AR outdoors in a large scale for design, construction and maintenance of AEC industry. In order to evaluate and compare the errors of the single marker method and the four-marker method, a series of experiments were performed. The result showed that the four-marker method showed much better performance compared with the single marker method. Then, we executed regression analysis and obtained a dimensionless equations for the given condition so that we could estimate errors for the future usage.

For future work, this method should be applied to actual design, construction or maintenance project of buildings or civil infrastructures.

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VISUALIZING CONSTRUCTION PROCESSES USING AUGMENTED REALITY: FUSING BIM, VIDEO MONITORING AND LOCATION INFORMATION

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ABSTRACT: *The current paper proposes a new approach based on Augmented Reality to visually fuse the data from different sources including a Building Information Model, video monitoring, and a Ultra Wide-Band (UWB) Real Time Location System (RTLS). The proposed method can be used to better visualize construction processes and to retrieve information about the time, space, and activities of a construction project. The benefits of the data fusion from different resources are discussed in terms of safety, quality, productivity and security of the project.*

KEYWORDS: *Augmented reality, construction processes, data fusion, BIM, location information, video monitoring, visualization.*

1. Introduction

Several methods can be used to model the information of construction processes and to monitor the execution progress of these processes. Among these methods, Building Information Modeling (BIM), video recording, and location tracking of construction resources have been extensively studied in recent research. BIM allows to model the components of a building in 3D and to visualize the sequence of the construction processes by linking the schedule information to the 3D model, resulting in a 4D visual simulation (4D BIM, 2011). However, because of the changes in the project conditions (bad weather, late delivery of resources, etc.), it is necessary to update the schedule by monitoring the progress of the construction work using manual or automated methods. Video monitoring has been used to record and monitor construction activities for the purposes of claim resolution and for studying the overall performance of the construction project using time-lapse photography (Abeid and Arditi, 2002; Chae and Kano, 2007). Location tracking of construction resources has been suggested as an effective method for progress monitoring (Navon and Sacks, 2007). More recently, location tracking of resources has been proposed by several researchers to capture deviations from the schedule or other changes in the project. Several technologies have been investigated for location tracking including the Global Positioning System (GPS) (Riaz et al., 2006), Radio Frequency Identification (RFID) (Chae and Yoshida, 2008), and Ultra-Wideband (UWB) Real Time Location Systems (RTLS) (Cho et al., 2010).

Each of the above automated methods (e.g. video and RTLS) can provide useful information about the construction processes and has certain advantages and disadvantages. Video monitoring provides a rich visual source of information that can be used by a human observer or can be automatically processed to extract features using video processing techniques (Chae and Kano, 2007). However, processing the video contents is complex and has several limitations (e.g. video occlusion) and does not identify individual workers captured in the video. RTLSs, on the other hand, can identify the individual construction resources (workers, equipment and materials) and their locations over time. However, they do not provide the contextual information about the actual work performed using these resources. Therefore, video and RTLS can be integrated with BIM to provide better understanding of the progress of construction processes.

The current paper aims to propose a new approach based on Augmented Reality (AR) to visually fuse the data from BIM, video, and UWB RTLS in order to better visualize construction processes. AR augments real-world views with digital data in real time by overlaying these data and views in a way that enhances the user's perception of reality. The objectives of this paper are: (1) to identify the potential benefits of integrating BIM, video monitoring, and RTLS in an AR application for visualizing construction processes; (2) to investigate the technical feasibility of this integration; and (3) to validate the proposed approach using two indoor construction case studies.

2. Literature Review

Managing activities and demands on construction sites is not an easy task due to the dynamic conditions and the different stakeholders participating in the projects. Opportunities for efficiency improvement were identified when time, money, and resources are wasted in situations such as the following examples: the workplaces are crowded, the crews are not on time due to lack of communication, the different resources such as materials and equipment are not easy to locate and need to be moved several times. That waste could be reduced if information technologies are applied to obtain real-time project information (National Research Council, 2009).

2.1 AR and data fusion in construction

AR integrates a real-time view of the user's environment and virtual objects within the same environment. Either the real view or the virtual view can be used as a background while the other type of objects can be superimposed and form a composite view. AR can extend the perception capabilities of the user in the real world and his or her interaction with its objects, providing information that the user cannot detect personally and directly (Izkara et al., 2007). AR has been used in construction for supporting bridge inspection (Hammad et al. 2002), for visualizing construction equipment operations (e.g., Behzadan et al., 2008), for supporting the interaction of two users operating two virtual cranes and communicating with each other (e.g., Hammad et al., 2009), and for automatic construction progress monitoring (e.g., Golparvar-Fard et al., 2009).

Data fusion was initially defined by the U.S. Joint Directors of Laboratories (JDL). Data fusion involves combining information in the broadest sense to estimate or predict the state of some aspect of the universe (Steinberg and Bowman, 2001). Shahandashti et al. (2010) have reviewed some examples of recent applications of data fusion in civil engineering and have presented some of the potential benefits, such as enhancing confidence, improving system reliability, reducing ambiguity, improving detection, extending spatial and temporal coverage in sensing systems, and increasing dimensionality.

2.2 Location tracking using ultra wideband technology

UWB is an RTLS wireless technology for transmitting large amounts of digital data over a wide spectrum of frequency bands at very low power (less than 0.5 milliwatts) (Ghavami et al., 2004). Researchers have started to investigate the usability of UWB on construction sites. For example, Teizer et al. (2007) have investigated the usability of a UWB tag attached to a crane hook to track the position of the hook. Giretti et al. (2009) have indicated that UWB behavior is rather constant during most parts of the construction progress. They have noted that, in an open area, tests confirm an accuracy of about 30 cm. Fullerton et al., (2009) have proposed using UWB for proactive safety, which works in real time to alert personnel of the dangers arising, and for reactive safety, which collects data to be analyzed in order to determine the best practices and to make process improvements. Carbonari et al. (2009) have proposed safety management systems for tracking workers' trajectories to prevent accidents. Cho et al. (2010) have discussed error modeling for an untethered UWB system for indoor construction asset tracking. Zhang et al. (2010) and Rodriguez et al. (2010) have discussed the feasibility of tracking construction resources for better productivity and safety on site.

2.3 4D BIM

Schedulers can create, track, and edit 4D models more frequently by using BIM, which can provide more reliable schedules (Eastman et al., 2011). Construction managers would have more time to coordinate other tasks, and the schedule misinterpretation would be mitigated via the visualized schedule by linking the 3D model and schedule. To generate a BIM schedule simulation, a 3D model of the building components has to be linked with the desired schedule. This simulation represents the construction processes in a virtual space from the start to completion. The provided animation helps the subcontractors and trades to realize the scope and timing of their assigned works, communicates the completion dates to the owner, and determines if the project is on track or not (Hardin, 2009).

3. Proposed Approach

3.1 Methodology

In this paper, it is proposed to attach UWB tags to workers and equipment that need to be monitored on site. The UWB RTLS records the tags' IDs and locations with the timestamps when the data was collected. Video cameras are installed at specific locations monitoring the site. The video camera records the activities within specific duration, where each video frame has a time stamp. For simplification, it is assumed that there is only one fixed camera used for monitoring one area, e.g., a room. Multiple cameras with pan-tilt-zoom functions can be used to extend the view of the video monitoring. Meanwhile, it is assumed that an as-planned BIM model is available, which includes the 3D environment model, task schedule, and resource allocation. Related to the task schedule, another resource database is also available, which indicates the resources needed for specific tasks in terms of labor, equipment, and material. Worker IDs, equipment IDs, and other attributes are stored in the database, such as the name of the subcontractor company, type of trade, wage of worker, rental cost and capacity of equipment, etc. Each of these different data resources includes only part of the task, space, and time information, which need to be fused to form an integrated database.

Fig. 1 shows the concept of the proposed methodology, where data from different resources are fused. The BIM model is simulating the construction environment, while the locations of workers and equipment are shown in the model with a specific update rate (e.g., 1 Hz). Videos are embedded in the model by creating virtual cameras in the BIM environment and linking them with the real cameras installed in the area. The BIM model includes a 3D model of the environment, schedule of construction activities, and the task IDs. A resource database are linked with the BIM model indicating the resource allocation for each task, for example, the number of workers involved in carrying out the task and the type and number of equipment used. Using the integrated database resulting from data fusion, queries can be made to retrieve the information of time, space and events of construction activities. For example, a query can be formulated to retrieve the video frames containing certain workers or equipment during a specific period. The input of the query is the IDs and the time period, while the output is the relevant video frames. This type of queries can be used for claim arbitration to investigate the specific workers or equipment involved in a certain conflict. Another type of queries can be used to retrieve the IDs of all workers or equipment and the corresponding video frames during a specific period. The input of a query of this type is the time duration, while the output is the IDs and video frames. This type of queries can be used for security purposes to check if an unauthorized person entered a specific restricted area.

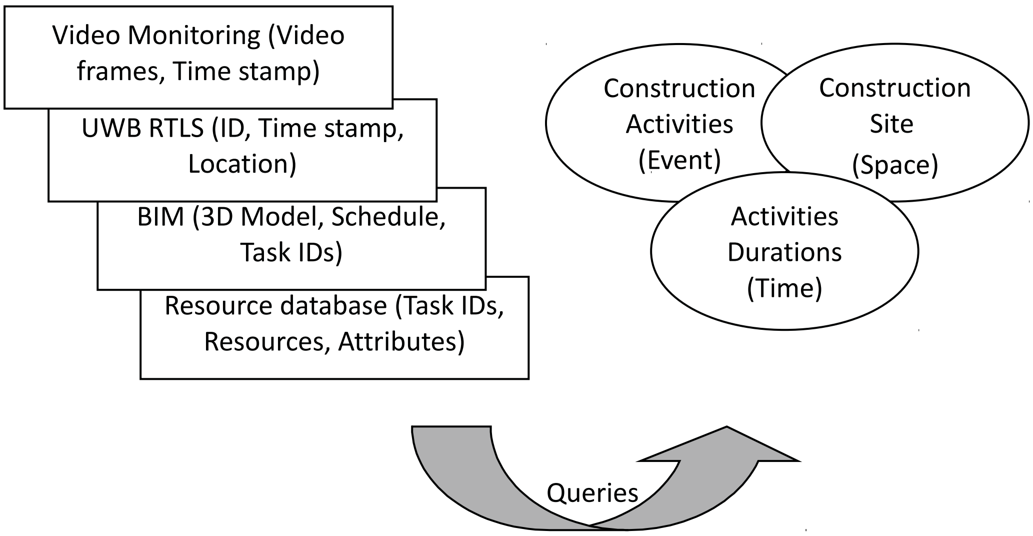

Fig. 1: Conceptual methodology.

3.2 Computational aspects

The process of fusing the BIM, video and UWB data is done through six steps as shown in Fig. 2:

(a) Loading the 3D model of the space which is going to be monitored.

(b) Adding a virtual camera in the 3D model by using the location P_0 (x_0, y_0, z_0) and orientation of the actual camera. The orientation can be found by measuring another point P_1 (x_1, y_1, z_1) on the center line of the camera and taking the vector $P_0 P_1$. These two points can be measured using the UWB system by attaching two tags to the camera.

(c) Adjusting the Field of View (FOV) of the virtual camera according to the FOV and focal length of the actual camera. As shown in Fig. 3 (Wikipedia, 2011), v and h are the height and width of camera frames, respectively. f is the effective focal length which, at infinity focus, is equal to the focal length of the lens *(f=F)*. The horizontal and vertical FOVs (α_h and α_v) of the camera can be obtained using Equations (1) and (2). The FOVs of the BIM software camera (α'_h and α'_v) would be bigger than those of the actual camera (e.g. 1.2 times) to show parts of the virtual model surrounding the picture.

$$\alpha_h = 2\tan^{-1}\left(\frac{h}{2f}\right) \quad (1)$$

$$\alpha_v = 2\tan^{-1}\left(\frac{v}{2f}\right) \quad (2)$$

(d) Adding a screen, on which the video frame will be displayed, perpendicular to the virtual camera center line. The distance of the screen from the camera can be obtained by calculating the nearest intersection of the shape representing the pyramid of the FOV of the camera with the boundary of the space. Fig. 2(b) shows an example of locating the screen in 2D at a distance d from the camera location Po.

(e) Adding the video frame to the screen, so by rendering the pre-defined view in the BIM software, the as-planed and as-built conditions, which are overlapped, can be compared as will be demonstrated in the case study. The picture is made transparent on top of the 3D model to make the comparison possible.

(f) Adding the traces of moving objects (i.e. workers and equipment), captured by the UWB system, to the model. Furthermore, some of the attributes of the moving objects can be displayed on top of the video at a specific location obtained from tracking. For example, the ID of the workers or the type of equipment can be added to augment the scene with information about the moving objects. This integration of UWB data with the 3D model needs applying a transformation matrix (translation, rotation, and scaling) between the two coordination systems of the UWB system and the 3D model.

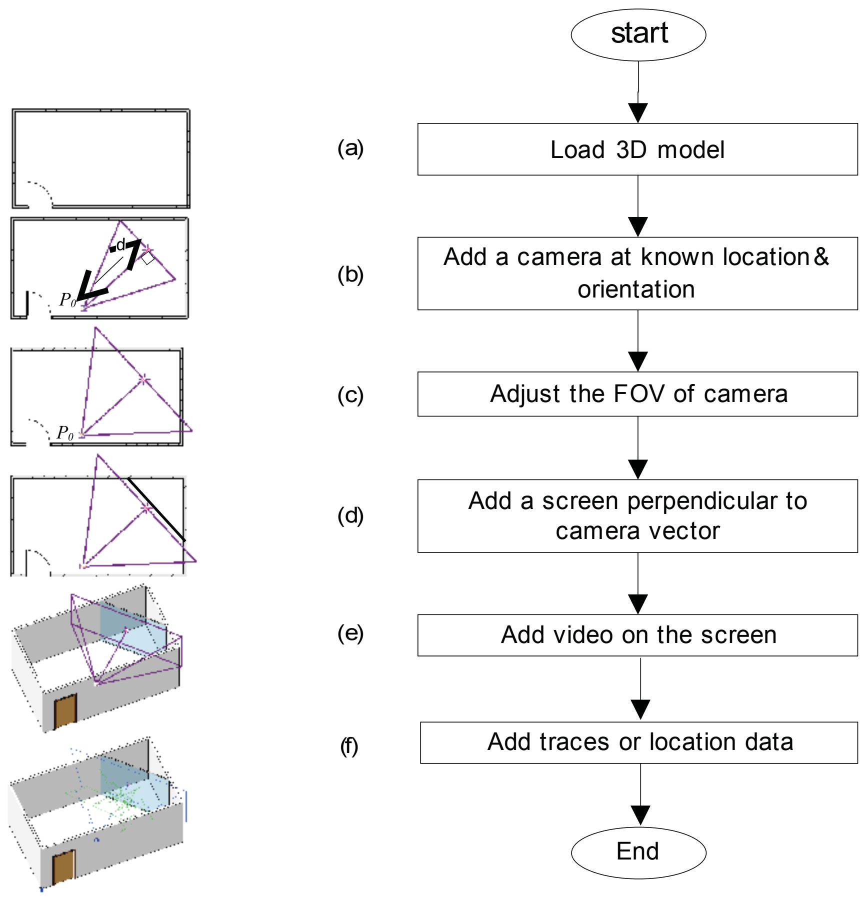

Fig. 2: Steps of proposed approach

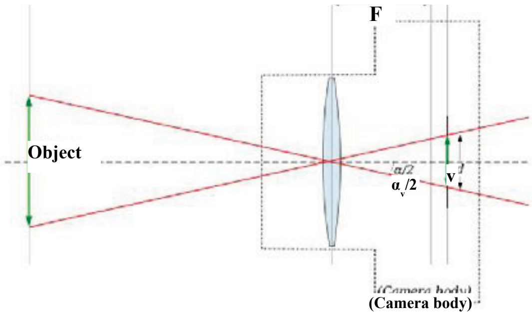

Fig. 3: FOV and focal length of a camera (Adapted from Wikipedia, 2011)

3.3 Benefits of data fusion

The main benefits of the proposed data fusion method are improving safety, monitoring productivity, quality control, and security. From the safety perspective, a construction site is dynamic, which requires continuous monitoring and updating of the location of all moving objects, including equipment and workers, to mitigate safety risks. For example, to reduce the risk of the workers entering a dangerous area, virtual fences can be generated to identify these areas according to the task schedule and safety regulations. The location of the tag attached to the worker is updated in real-time, and the distance between the tag and the virtual fence is calculated. Once the distance is less than certain threshold, an alarm will be sent to the worker to reduce the safety risks. From the productivity perspective, the location data of each worker can be analyzed to find the patterns of how the workers perform their tasks. From the quality perspective, the as-built construction model can be compared with the as-planned model, by checking the videos captured during construction. From the security perspective, it is possible to detect unauthorized personnel in restricted areas through querying the integrated data of RTLS and videos as explained in Section 3.1.

4. Implementation and Case Studies

4.1 Implementation

The models of two existing spaces have been developed in Revit Architecture 2010 to provide the as-planed conditions. Ubisense sensors are used as the UWB system to capture location and orientation of the actual camera in addition to the traces of workers. An interface is developed to import UWB data to Revit using Revit and Ubisense APIs. A fixed Canon camera FOV is used to take photos of construction progress. Currently, only pictures captured from the camera are integrated into the BIM model. However, the same technique can be applied to videos in the future. By using Equations (1) and (2), the horizontal and vertical FOVs of the actual camera can be obtained and used to adjust the Revit camera. A 35 mm camera with a normal lens can have up to 50 mm focal length. The frames of the 35 mm cameras are 36 mm × 24 mm. The Revit camera's FOV is 50 degree by default as is shown in Fig. 4. The FOV and effectively the focal length of the Revit camera can be obtained according to Equation (3) (Pacific, 2011).

$$\text{Focal length} = \frac{0.5 \times \text{film dimension}}{\tan\left(\frac{FOV}{2}\right)} \tag{3}$$

By keeping the Revit camera's default settings, the Revit camera is equivalent to a 38.6 mm focal length lens (Pacific, 2011).

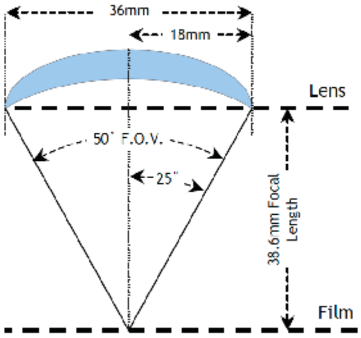

Fig. 4: The default Revit camera's focal length (Pacific, 2011)

4.2 Case studies

In the first case study, a room with 3 m height, 4 m width, and 7 m length is modeled in Revit Architecture 2010. Fig. 5 shows the floor plan of the room and the connections between four sensors. The solid lines show the data cables connecting the sensors with the Power over Ethernet (PoE) switch, whereas the dotted lines show the timing cables. The installation of wall shelves is monitored in this case study. The camera is used to take photos of the installation progress and provide the as-built condition. The real camera is oriented toward the part to be monitored. Data related to the location and orientation of the actual camera are applied in Revit Architecture to define the location and orientation of the Revit camera. Fig. 6 shows the picture taken by the camera on top of the virtual model.

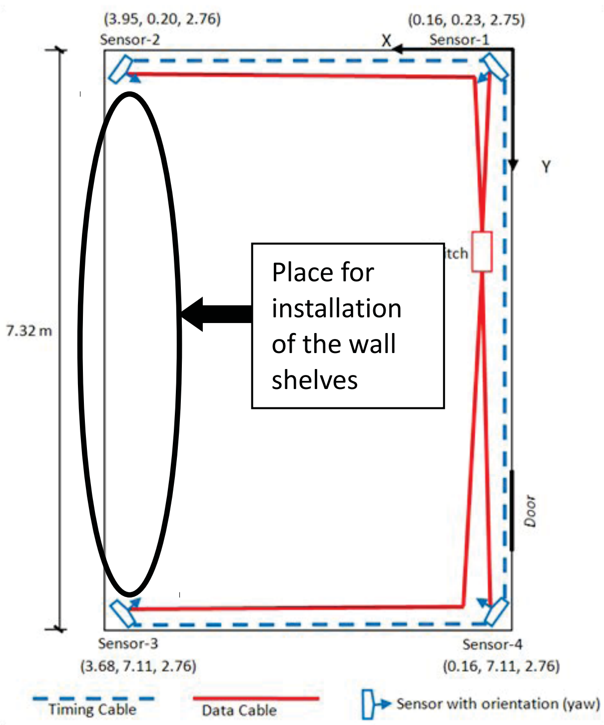

Fig. 5: Floor plan of the room and the setting of the UWB system

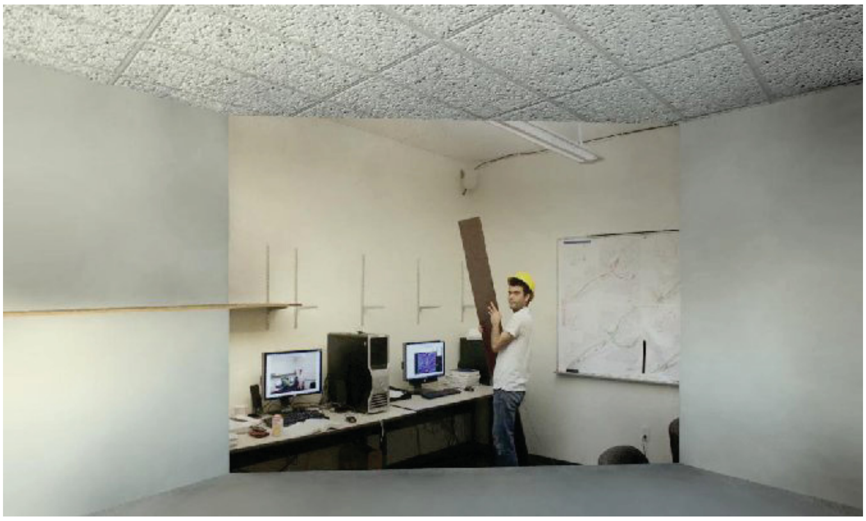

Fig. 6: Augmented reality view of the task of shelves installation

The second case study is used to demonstrate the proposed approach focusing on the tasks of installing HVAC ducts on the 7th floor of the JMSB Building of Concordia University as shown in Fig. 7. A BIM model of the floor and the ducts has been developed using Revit Architecture and Revit MEP, respectively. The installation work in one part of the floor has been monitored with a video camera and two workers in that part have been tracked using a UWB system. The information of BIM, the video monitoring and the UWB traces are processed as follows: (1) The BIM model is used to provide a spatial reference and to show the ducts that have been already installed and those that will be installed in the next few hours using different colors; (2) The pose of the virtual camera within the BIM software is adjusted to match the pose of the actual camera; (3) The collected traces of the movements of the workers are processed to fit over the scene; and (4) The current locations of the workers as identified in the UWB data are used to augment the scene with information about the workers and their planned tasks.

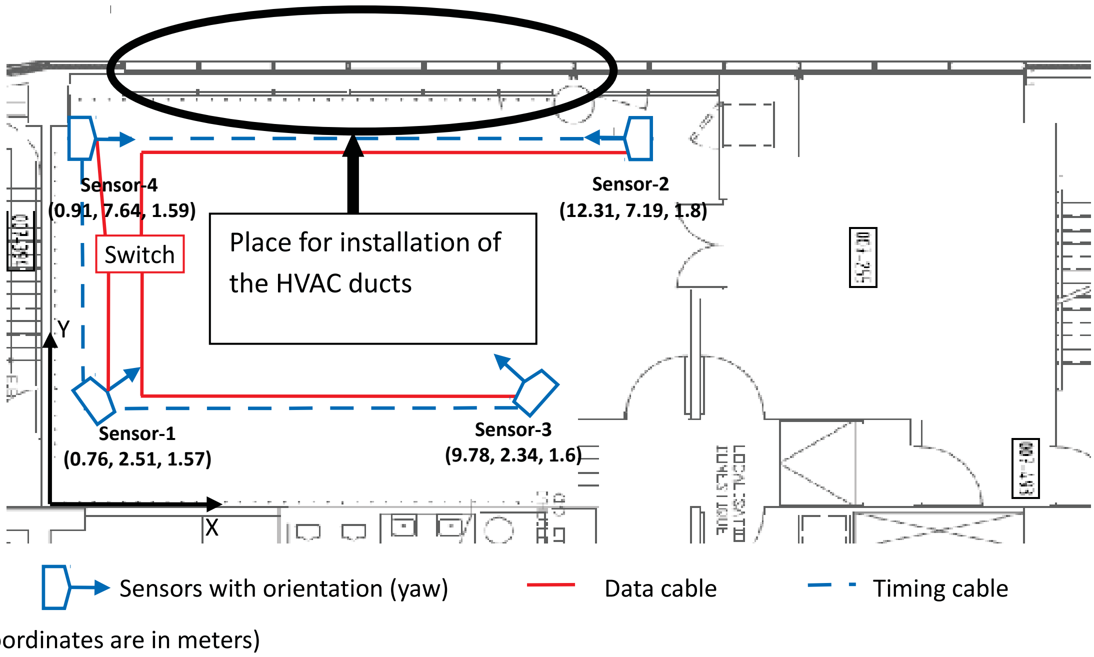

Fig. 7: Floor plan of the construction site and the setting of the UWB system

Fig. 8 shows the interface for selecting and loading the UWB data into the 3D model. It provides tag IDs and their coordinates at specific dates and times. The trace of each tag can be imported in Revit. The location, angle, and scale of traces can be adjusted through the interface as transformation should be applied on data captured from the UWB system to fit into the coordinate system of Revit. Fig. 9 shows an AR view of the workers and their traces. Each of Traces show the locations of a specific worker for a short duration. Fig. 10 shows an example of augmenting the BIM model with a picture of the workers and their IDs. The IDs and their locations are extracted from the UWB data.

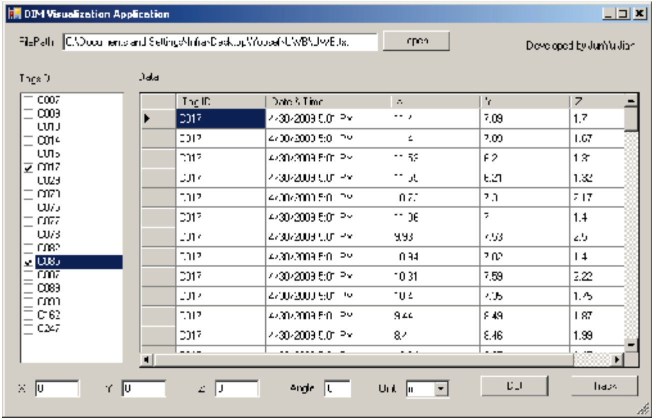

Fig. 8: Revit interface for adding UWB data

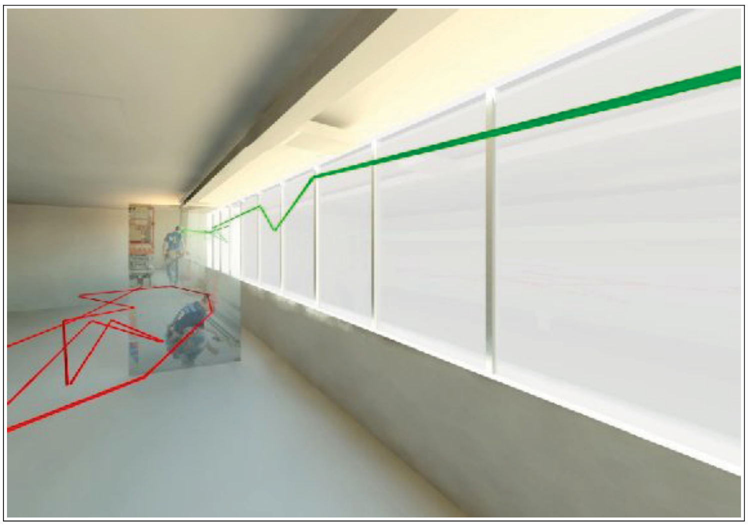

Fig. 9: Augmenting the BIM model with picture of workers and the traces of their movement

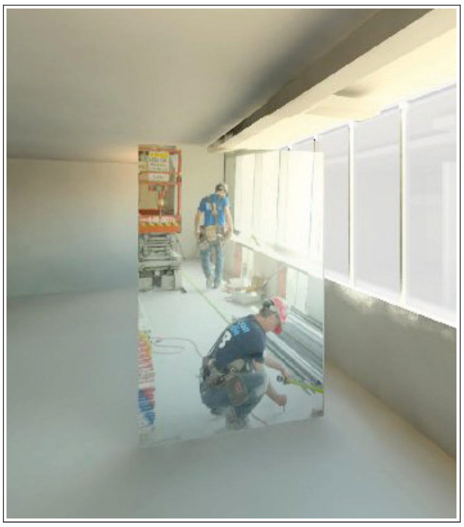

Fig. 10: Augmenting the BIM model with video of workers and their IDs

5. Conclusions

The current paper presented a new approach based on Augmented Reality (AR) to visually fuse the data from BIM, video, and UWB RTLS in order to better visualize construction processes. The potential benefits and the computational steps of this data integration have been discussed. Two case studies have been used to demonstrate the feasibility of the proposed method. However, further studies and testing are needed to fully develop the practical applications of the proposed method.

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ON-SITE logisticS SIMULATION IN EARLY PLANNING PHASES

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ABSTRACT: *Logistics processes have a large impact on the planning and execution of large-scale or inner-city construction projects. The application of discrete-event simulation is a common way to analyze different logistics scenarios in order to prove the feasibility of time schedules and identify bottlenecks. The data preparation is one of the main challenges during the simulation of construction logistics processes because of the unique characteristics. In early planning phases especially, only elemental information about activities, deliveries, and resources are available. An innovative concept to extract and prepare input data for logistics simulation in early planning phases is presented in this paper. The so-called Mefisto container is used to integrate essential project data. In the next step, the project data is analyzed and prepared by an additional software tool, the so-called SiteSimEditor. Based on the extracted and prepared data a simulation model can be generated by using configurable simulation components. The resulting simulation model contains information about the construction site layout and logistics processes. The concept was validated by a case study, which comprises the shell construction of an airport terminal.*

KEYWORDS: logistics simulation, simulation input data preparation, construction management, discrete-event simulation, early planning phases.

1. Introduction

Logistics processes often play an important role during the planning of construction projects, especially in large-scale or inner-city projects. In these cases, construction clients often define certain demands concerning delivery or on-site logistics, for example, restricted delivery and working times or arriving limits of trucks per day. In early planning phases especially, one of the main challenges is the consideration of the given logistics restrictions in an appropriate way. Usually, only general project data exists in these phases with low details regarding building elements, construction processes and required resources. In consequence, the integration and specification of reliable logistics information is not trivial. Logistics restrictions have significant effect on construction process and cost estimation. Delays often occur due to insufficient analyses of logistics processes and their restrictions. The analysis of the influences of logistics aspects on the construction processes in early planning phases allows discovering limitations in terms of the project schedule. In the last decades, discrete-event simulation became an important method of analyzing production and logistics processes and their dynamical interdependencies (Wenzel et al. 2010). Thereby, a simulation model can be used to specify a number of different logistics and construction scenarios. Typical functions of logistics simulation in early stages of planning are (Spieckermann et al. 2010):

- Generation of time schedules based on material flow specifications, milestones and framework dates, and available resources. All these restrictions must be integrated and satisfied in an optimal manner.
- Evaluation of different logistics concepts and identification of possible bottlenecks. This comprises alternative storing and transportation strategies.
- Analysis of reliability and robustness of time schedules by considering possible disturbances and uncertainties regarding the available project data.

Today, logistics simulation plays only a minor role in the context of construction management. The main reasons are unique building designs, varying construction site locations and individual construction processes. Furthermore, construction logistics processes are more dynamic due to varying construction site conditions. For these reasons the simulation of construction and logistics processes requires a large effort for modeling and data preparation (Kugler et al. 2009). The collection and preparation of reliable and reasonable input data for logistics simulation is very time-consuming and requires special knowledge. Bill of quantities, first drafts of the construction site layout, and general information about the construction processes are often the only available project information.

In order to support the project planners during the specification of appropriate logistics simulation models, the *Mefisto* project was funded by the German Federal Ministry of Education and Research. *Mefisto* stands for data integration, simulation, controlling and prediction in construction management. The main objective is the development of an integrated multi-level data container concept to handle different data models during all planning phases. Thereby, the so-called *Mefisto* container links all data models in a consistent and adaptable way (Scherer et al. 2010). Within the sub-project "knowledge-based simulation modules", certain project data is extracted and used for the preparation of input data to simulate construction and logistics processes. However, in most cases the project data is not sufficient to generate significant simulation models. In addition, material dimensions, packing units, means of transportations and logistics chains must be added. In the next step, this logistics data can be used to produce a specific simulation model and to define the input data for the simulation scenarios.

A concept for extracting, defining and preparing data is presented in this paper in order to create significant logistics simulation models. Configurable software modules are used to define the simulation model for a unique construction project. Furthermore, input data for simulation experiments are prepared and generated by an external tool. Using this concept, realistic logistics scenarios can be set up more time-efficiently to support the construction planning.

2. LogisticS Simulation

Logistics simulation can be used to analyze specific aspects during the construction of a building. In general, the focus lies on simulating the material flow. That means that certain material elements are delivered, handled and stored on construction sites. It is also possible to combine production and logistics simulation. Thus, production processes of buildings are also taken into account. In the paper, only the simulation of logistics processes is considered. Similar data must be prepared nearly for every logistics simulation. This data comprise transport ways, transport equipment, storage areas, delivery dates, packing units, and transport chains. Usually, static transport ways and storage areas are used in the context of logistics simulation. Due to the building itself and other external site effects, it is also possible that transport ways and storage areas can change during construction. In the presented concept, only static ways, storage areas and transport chains are considered.

Abstracted, predefined, and configurable simulations components can be used in order to implement logistics simulation models. Nearly every commercial material flow simulation tool provides elements to support the user during the implementation process. However, these components generally are highly abstract and hard to use in particular for construction simulation. Therefore, additional components and frameworks are often developed for special purposes to overcome these drawbacks. The *Simulation Toolkit Shipbuilding* (*STS*) is a holistic component-based simulation framework, which has also some special components for the construction industry. The *Simulation Toolkit Shipbuilding* was developed by Flensburgers, a German ship building company (Steinhauer 2006), based on the commercial simulation engine *Tecnomatix Plant Simulation* by Siemens PLM Software. This toolkit comprises several components to model construction and logistics processes at shipyards. The classes were adapted for construction processes in cooperation with the Ruhr-University Bochum, the SimPlan AG, and the Bauhaus University Weimar. The *STS* also provides a so-called constraint-based modeling approach. That means that restrictions for executing processes are formulated based on certain constraints (König et al. 2007). Thereby, so-called hard and soft constraints can be considered. Hard constraints are used to model necessary restrictions which must be satisfied, for example, technological restrictions. Soft constraints can be used to implement different scenarios or strategies, on how the construction process should be executed. This concept offers a generic way to generate models of logistics and construction processes in different levels of detail. Fig. 1 highlights some typical simulation components to simulate logistics processes.

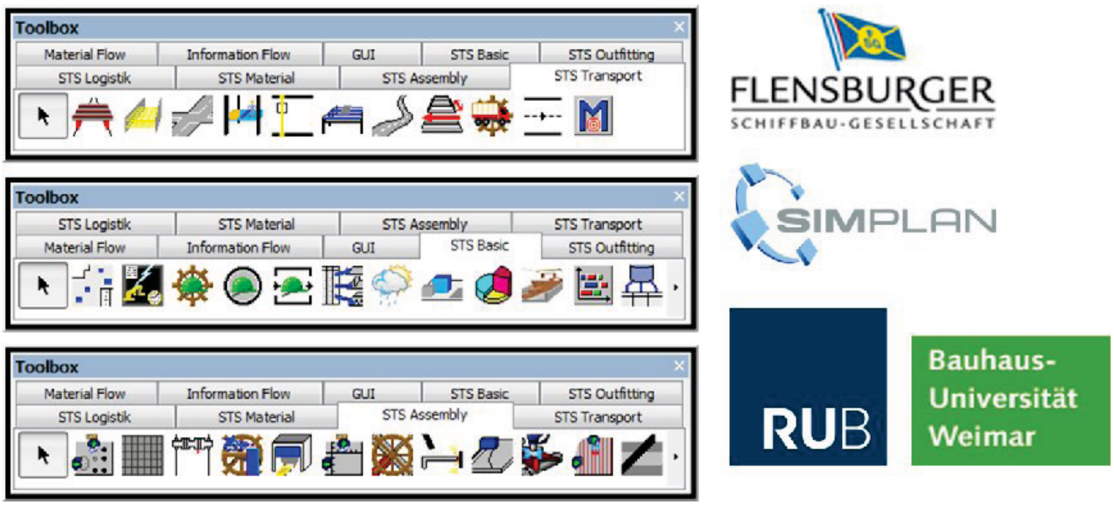

Fig. 1: Components of the Simulation Toolkit Shipbuilding for simulating logistics processes

The *STS* components are used to implement logistics simulation models for early planning phases. In addition to the components values for the configuration are needed. For example, dimensions, locations, and rules of the transport ways must be specified as well as operation values and machine data. Furthermore, transport and logistics chains need to be modeled, for example, which storage areas can be handled by which cranes or where unloading positions are located for certain material elements.

2. Integrated Data Preparation

Generally, the data preparation is the main challenge within the realization of simulation models and scenarios. Thereby, some of this data is used to generate the simulation model layout. Other data can be used as input data for experiments regarding desired objectives. Data collection and preparation is usually done in different successive steps. In the first step, the available information must be analyzed and prepared in terms of the defined goals. Levels of detail and data quality play an important role. In some cases, the simulation objectives cannot be reached due to the available data. In the next step, additional information has often to be defined manually. For example, if material dimensions and packing units are not known to analyze storage bottlenecks, then the only possibility is to generate realistic data using some reasonable assumptions. In the last step, the enriched data can be used to prepare simulation models and simulation scenarios for certain simulation frameworks. The three data steps, shown in Fig. 2, are supported by the so-called *SiteSimEditor* (Marx et al. 2011).

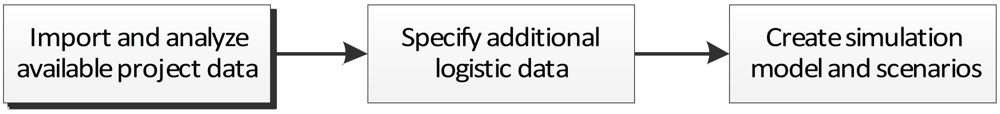

Fig. 2: Integrated data preparation for logistics simulation

During the first step all available project information is imported. The project information must be stored digitally to support reusing. Nowadays, standardized building information models comprise many required information for logistics simulation. However, essential data is often missing. Available data, which is normally necessary to set up logistics simulations, is highlighted in the following:

- Material quantities can be taken from building information models. For example, in-situ concrete, reinforcement steel, formwork, and pre-cast elements for shell construction activities can be calculated. Today, the material quantities and building elements are associated, so that delivery and storage locations can be derived.
- Milestone schedules and framework dates are often corporately specified by the client and contractors based on building information models. Thus general data or rather general activities can be linked to their corresponding building elements by using modern project management tools.
- Layout information about construction sites and the nearby environments (i.e., transport ways, storage areas, equipment, or existing buildings) are normally modeled digitally and are often basis of general contract.
- Sometimes special logistics restrictions are defined a priori. Logistics restrictions can cover, for example, time windows for delivery, number of simultaneous trucks on the site, gateway checks, or storage of hazardous materials. This information is sometimes provided by the client.

Generally, the described data is not exclusively defined for logistics simulation. It can be used for different purposes during planning, construction and operation. In the last years consistent coupling and integration of project data models was in the focus of several research projects. In the *Mefisto* project an innovative concept for coupling different models on different levels of detail has been developed. Different models can be linked by using unique identifiers. Links are stored using XML in an external link model. Project data, link models and additional Meta information can be integrated into an archived ZIP-file, and forms the so-called *Mefisto* container. Each project can contain several *Mefisto* containers for different purposes. One special container was implemented to support the data collection und preparation for logistics simulation. This Mefisto container covers, among other data, *IFC*-based building information models (*IFC* STEP format), bill of quantity (BoQ) files using the German *GAEB* standard (*GAEB* XML format), model-based quantity takeoffs (QTO), construction site layouts including construction equipments (*Mefisto* XML format), and general activities and milestones (*Mefisto* XML format). Further information about the *Mefisto* container and different used data formats can be found in Scherer et al. (2010).

These essential data models are linked to provide the required information for the logistics simulation. Starting with the general construction activities, for each activity the required material quantities can be extracted. For example, if a reinforcement activity of a building section is processed, the calculated steel in kilogram can be determined. Furthermore, the general location of an activity on the construction site can be calculated using the building information model, and consequently to find an appropriate storage area. Some typical model links for logistics simulation are shown in Fig. 3.

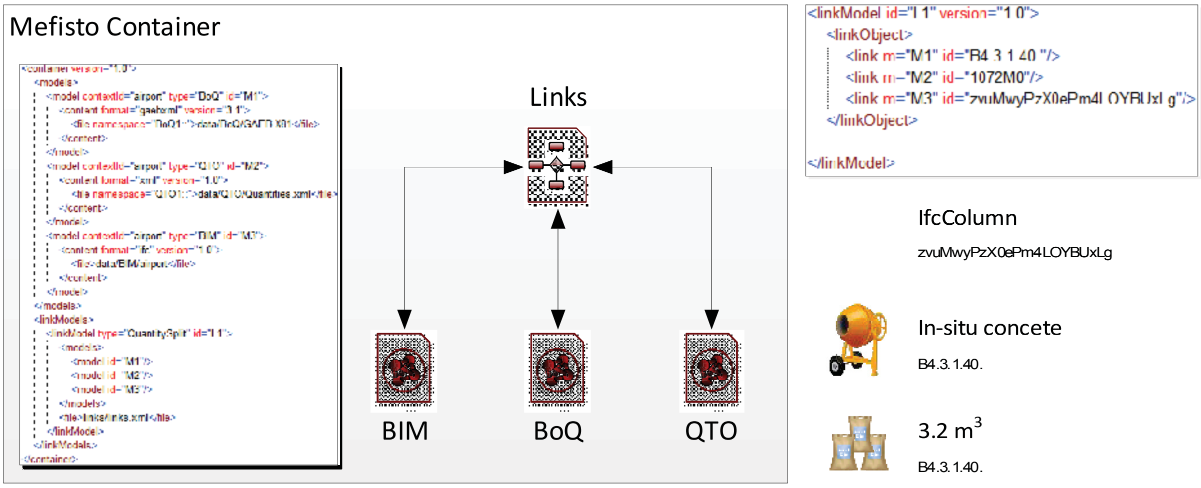

Fig. 3: Mefisto container to support the collection and preparation of logistics simulation

Using information about construction site layouts, general transport ways, storage areas, gates, and equipment including their positions can be extracted to set up a simulation layout. The described *Mefisto* container for logistics simulation is also used to define additional input data. Very important are the specifications of delivery dates, means of transportations, material quantities, and packaging units. Normally, this logistics data is not needed for any other purpose than logistics simulation. Therefore, it must be defined manually by planners. However, in the early phases of planning detailed information about deliveries is often unknown. Consequently, the planners use their experiences and reasonable assumptions for their definitions.

In the *Mefisto* project the *SiteSimEditor* has been implemented to support data preparation and definition processes. Necessary input data can be filtered from the *Mefisto* container and clearly visualized. The *SiteSimEditor* provides an intuitive and flexible user interface for definition of the additional logistics data. The material quantities can be listed for each general activity. Next, typical packing units are specified. Information about common packing units for certain material can be selected form an internal knowledge database. This database can be extended by the user. The means of transportation can be typed in based on the defined packaging units. For example, formwork and reinforcement steel meshes can normally be transported by different trucks and cast-in-place concrete by concrete mixers. The SiteSimEditor uses the quantities and the packing units to calculate the required number of transports for the selected vehicles. Usually, the material is not delivered simultaneously. In fact, it is distributed over time while taking the underlying activity into consideration. The *SiteSimEditor* provides interfaces, with which the user can define certain distribution functions and reasonable handling times. If additional restrictions, like time windows or arriving limits of trucks per day, have to be taken into account, these conditions can also be specified beforehand and considered during the generation process. As a result the daily amount of vehicles, which must be handled on the construction site, are available for logistics simulations (cf. Fig. 4).

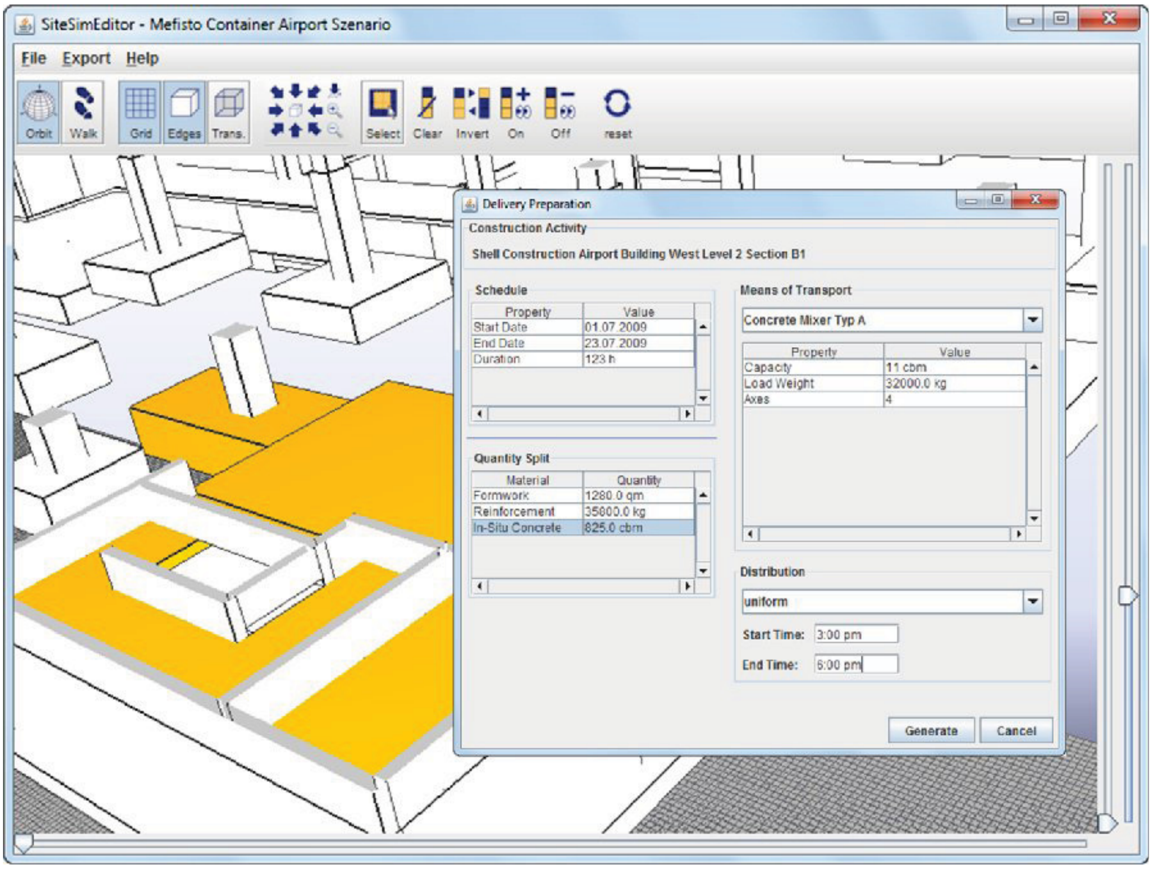

Fig. 4: Specification und generation of delivery data for logistics simulations

Further information must be defined in order to model transports on the construction site. Usually, arriving vehicles are unloaded at certain positions. Subsequently, the delivered material is stored on default storage areas or is processed directly like cast-in-place concrete or pre-cast elements. On construction site cranes are often used to unload the material. The integrated consideration of vehicles, unloading positions, storage areas, production locations, and cranes is called logistics chain. A logistics chain must be defined for each delivery. During the logistics simulation, the optimal transport way to its destination is automatically calculated for each arriving vehicle. The logistics chains are specified based on the imported construction site layout. For each generated vehicle or a group of vehicles the associated logistics chain can be interactively defined by selecting unloading positions, storage areas, and cranes for unloading. If the delivered material is to be processed directly, the unloading positions can be calculated by analyzing the corresponding building elements of the building information model.

Usually, several scenarios are modeled comprising varying transport processes and logistics chains. Each scenario must be simulated and analyzed separately. Therefore, the *SiteSimEditor* provides functionalities to manage and store different data sets. For this reason a simulation input database was implemented, which also serves as interface for the connected simulation framework. However, the simulation framework must also be extended to process the input data for model generation and running experiments. In our case, Tecnomatix Plant Simulation from Siemens PLM is used as simulation tool in combination with components of the Simulation Toolkit Shipbuilding. Currently, the model generation must be done in an explicit way by establishing a connection to the database and executing a special import method. The simulation model must be created each time, when general modifications of construction layout are carried out. Afterwards, a simulation scenario can be selected and executed. The results, like waiting times on construction site of the vehicles, utilizations of cranes, or start and end times of the construction activities, are stored back into the simulation database and can be used for further analysis.

4. Case Study

The described concept was validated by a practical case study. The case study deals with logistics processes for shell construction activities of an airport terminal during full operation. The new airport terminal consists of six levels and has a total area of 185,000 square meters. The given framework time schedule includes 60 construction activities. The total shell construction time was estimated to be around 12 months.

The client defined several logistics restrictions. Essential restrictions are crane positions and storage areas due to existing buildings and on-going operation, fixed entry gates for trucks, maximal deliveries per day, and limited access and construction times. Construction site layout data were extracted and prepared using the *SiteSimEditor* based on an integrated *Mefisto* container for logistics simulation. The result of simulation model generation is shown in Fig. 6. The simulation models includes 16 cranes, 11 storage areas, 12 construction areas, 148 transport way elements, and one entry gate.

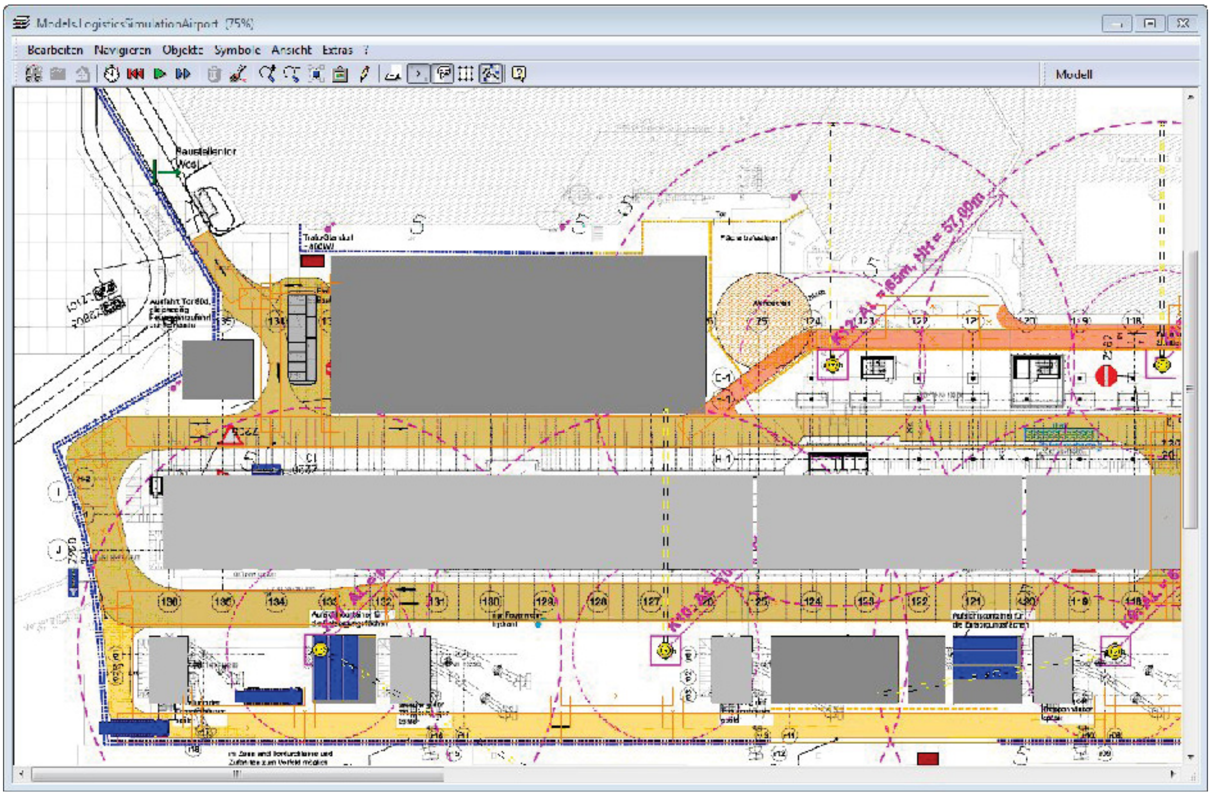

Fig. 6: Logistics simulation components of the airport construction site

In the next step, the main deliveries were specified. First, in-situ concrete, pre-cast elements and reinforcement steel were modeled und transported by different trucks through the entry gate to the cranes for unloading. Therefore, capacity information of the trucks was needed. For example, seven precast floor slabs can be carried by one truck or 8 cubic meter in-situ concrete by standard concrete mixer. The *Mefisto* container provides the estimated material quantities and elements for each construction activity by analyzing the links between building elements, construction activities, bill of quantities, and quantity take-off. More than 6500 deliveries were generated, that means about 25 deliveries per working day. The construction time was limited to 9 hours per day from Monday to Friday. Next, the deliveries were distributed over the activity durations taking limited access and construction times into account. In this case study a uniform distribution was used. Furthermore, priorities for certain deliveries were defined. If several trucks were arriving or waiting at the entry gate, then deliveries with higher priorities would be dispatched expediently. Typical priority deliveries are, for example, material for Just-In-Time (JIT) construction like in-situ concrete or large-size pre-cast building elements. Each delivery is related to an activity and the location where this activity takes place. However, the daily amount of deliveries often varies significantly. In Fig. 7 the daily delivery amount of reinforcement, in-situ concrete and pre-cast building elements highlighted.

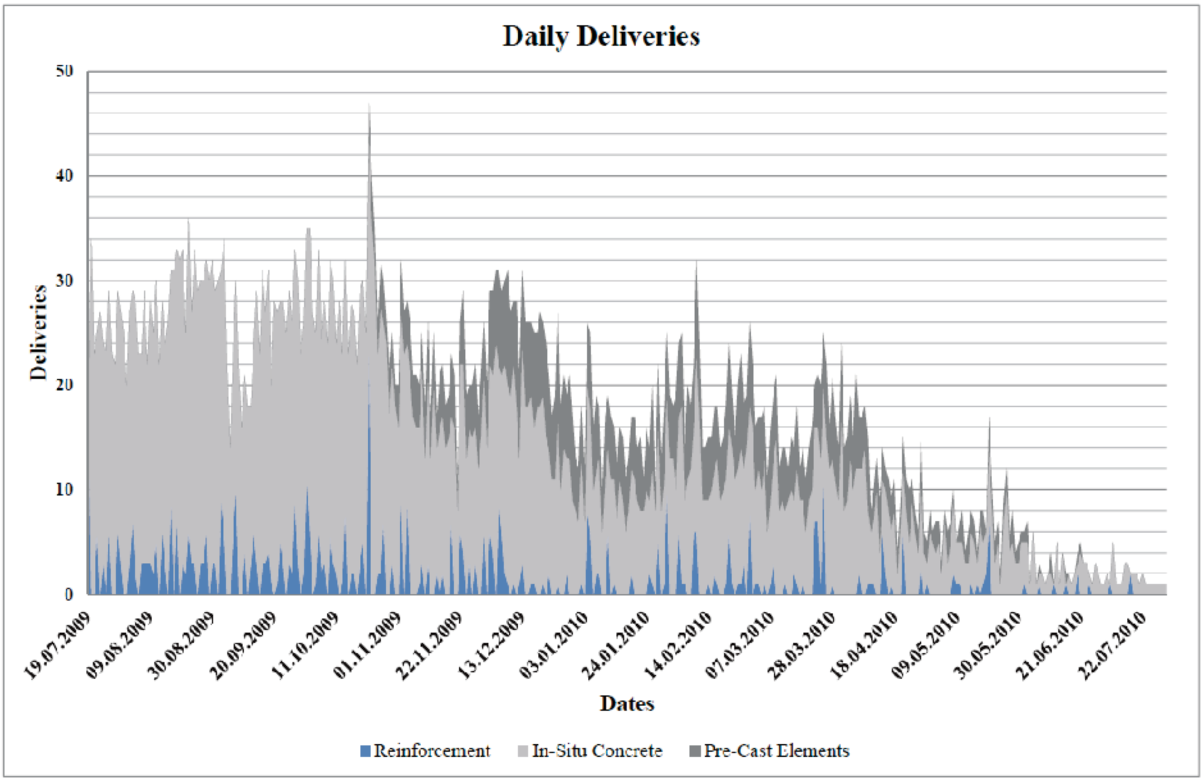

Fig. 7: Daily deliveries of reinforcement, in-situ concrete and pre-cast building elements

Different statistical data sets were collected during the simulation run in order to analyze the on-site logistics. The statistical data includes the utilization of resources, allocation of storage areas, transport and waiting times on construction site and entry gate. Fig. 8 shows the number of waiting trucks at the entry gate for each working day. The waiting trucks oscillate significantly in some time intervals. The parking space at the entry gate is limited to two trucks. Therefore, dates of deliveries to construction site have to allow for the processing time of the trucks.

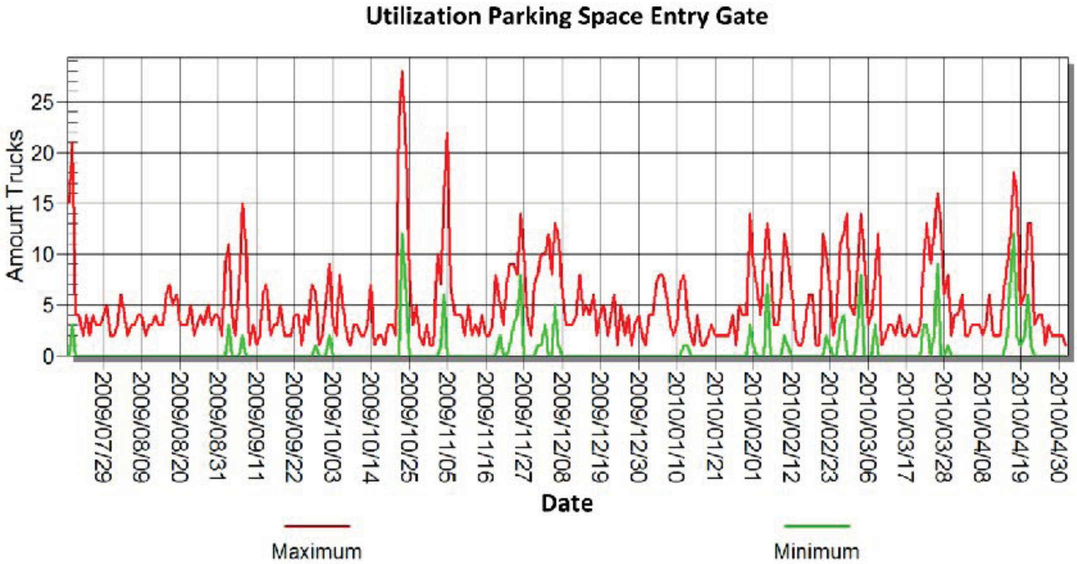

Fig. 8: Content of parking space of entry gate

In the next step the resource utilizations were analyzed in order to identify critical bottlenecks. For example, the weekly utilization of the concrete pump is illustrated in Fig. 9. The utilization correlates with the delivery amount of concrete. Critical bottlenecks were not identified.

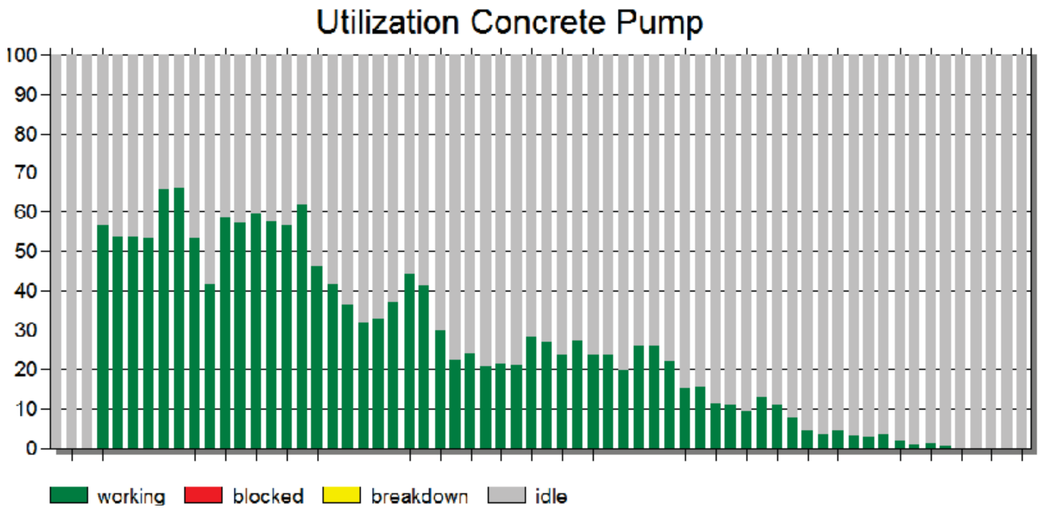

Fig. 9: Utilization diagram of the main concrete pump

5. Conclusions and Outlook

An innovative data preparation concept for logistics simulations in early planning phases is presented in this paper. Available project data is collected, integrated and linked to generate the necessary input data for logistics simulations. The basis of the data integration is the so-called *Mefisto* container, which enables links between different data models. The *SiteSimEditor* is used for data preparation and extension. Based on the prepared data the corresponding simulation model can be generated automatically using already implemented and configurable simulation components. Furthermore, the *SiteSimEditor* provides the input data for the simulation model like activities, deliveries and logistics chains. The presented data preparation and model generation approach allows the investigation of logistics processes of large-scaled construction project in an efficient way. The concept was validated by a case study considering the shell construction of an airport terminal. In the next step the definition and reusing of logistics chains will be addressed. Furthermore, the Mefisto Container for logistics simulation will be extended by general packing units and further equipment data.

The authors gratefully acknowledge the financial support of the German Federal Ministry of Education and Research for the *Mefisto* project.

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A CONSTRUCTION-TRANSPORTATION INTEGRATED SIMULATION FRAMEWORK BASED ON HIGH LEVEL ARCHITECTURE

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ABSTRACT: *Instead of construction of new roadways, highway 4-R works in terms of restoration, resurfacing, rehabilitation and reconstruction contribute a dominant portion of highway construction activities in many countries. This is especially true in Canada, where highway ages and deteriorates at a high rate due to various factors including the extreme cold weather. As highway 4-R works are typically conducted on existing road networks, it is important to find a methodology to facilitate making trade-offs among different factors including construction productivity, traffic satisfaction, road user cost, safety and so forth. This paper gives a review of current practices including industry practices, research developments, and case studies covering guidance, manuals, mathematic models, analytical methods, and computer tools. By comparing and considering the advantages and limitations of current practices, a Construction-Transportation Integrated SIMulation (CTISIM) framework for accessing highway 4-R work strategies is proposed. Its motivation is to combine the power of discrete event construction simulation with microscopic traffic simulation based on the High Level Architecture (HLA) which is an international standard for distributed simulation. Thus, a detailed construction model can communicate and interact with a sophisticate traffic model to get more realistic simulation results. As a preliminary case study, a ready-mix concrete (RMC) production and delivery problem is adopted to demonstrate the feasibility of the CTISIM framework. This paper sheds light on the further research on highway 4-R project management.*

KEYWORDS: *distributed simulation, high level architecture (HLA), highway construction, work zone, discrete event simulation, microscopic simulation, review*

1. Introduction

In Canada, highway ages and deteriorates at a high rate due to various factors including the extreme weather conditions. In US, each year, the Departments of Transportation (DOTs) have endless highway sections in need of restoration, resurfacing, rehabilitation and reconstruction known as 4-R type highway work zone projects (Bayraktar and Hastak 2009; Lee et al. 2005). Compared to construction of new transportation facilities, it is more challenging for DOTs to conduct the 4-R type highway projects, as most of them are located in congested urban areas with heavy traffic flow or on freeways with high-speed traffic vehicles. Highway construction works usually cause lane closures, which has a negative impact on traffic in terms of road user cost, safety, motorist satisfaction etc. As a feedback, the traffic flow has negative impact on construction duration, cost, safety etc. A significant body of research has been conducted to gain insights into the complicated interrelationships between highway construction work and the highway traffic. To achieve the construction project goal successfully, it is important to select an effective planning, scheduling and controlling system (Sharma et al. 2009).

This paper gives a review of current practices including industry practices, research developments, and case studies covering guidance, manuals, mathematic models, analysis methods, and computer tools. By comparing and considering the advantages and limitations of current practices, a joint construction-transportation simulation method for accessing highway 4-R work strategies is proposed. Its motivation is to combine the power of discrete event construction simulation with microscopic traffic simulation based on the High Level Architecture (HLA) which is an international standard for distributed simulation. Thus, a detailed construction model can communicate and interact with a sophisticate traffic model to generate more realistic simulation results. Particularly, this paper sheds light on the further research on highway 4-R project management.

2. Factors Affecting Highway Work Contracting Strategy

Compared to other construction projects, highway construction has a greater impact on our daily life. Thus, when planning a highway construction project, not only the direct costs of a construction project, but also indirect user costs (extra time spent on detour, traffic delay from highway construction) and the economic impacts on roadway users should be considered (Hardy et al. 2007) Bayraktar and Hastak (2009) summarized the main performance indicators of highway work projects in terms of cost, schedule, quality, safety, and public/motorist satisfaction. To achieve an optimized highway work contracting strategy, a bunch of factors should be considered. (cited from Bayraktar and Hastak 2009)

- technical factors (e.g., location, work zone length, work window, difficulty of work, site constraints, traffic volume, planned detour, and lane closure strategy),
- social/political factors (e.g., inconvenience to users, disturbance to nearby community, business disruption, public perception, and other political considerations),
- financial considerations (e.g., traffic maintenance cost, fuel cost, delay cost, accident cost, and liabilities),
- contractual requirements (e.g., type of contract, incentives, penalty, risk sharing, and other legal considerations), and
- Other factors (e.g., utility issues, right-of-way issues, and environmental permits).

A significant body of research has been conducted to evaluate and estimate the impact of the various factors and facilitate achieving trade-offs among multiple parties.

3. Practices and Research on Work Zone Strategies

In this section, the review of current practices and previous research are categorized under four topics, namely guidance and manuals, multiple factors analysis and decision-support models, deterministic macro level analysis, and stochastic operation level simulation. Normally, the guidance and manuals issued by the Department of Transportation (DOT) provide basic principles, base values or ranges of capacity for handling work zone configuration. Research work under the other categories covers various qualitative or quantitative analytical methods. According to Hardy et al. (2007), the relationships between different functionalities of work zone analysis tools are well illustrated in Fig. 1 (the names of modeling tools are shown in boxes).

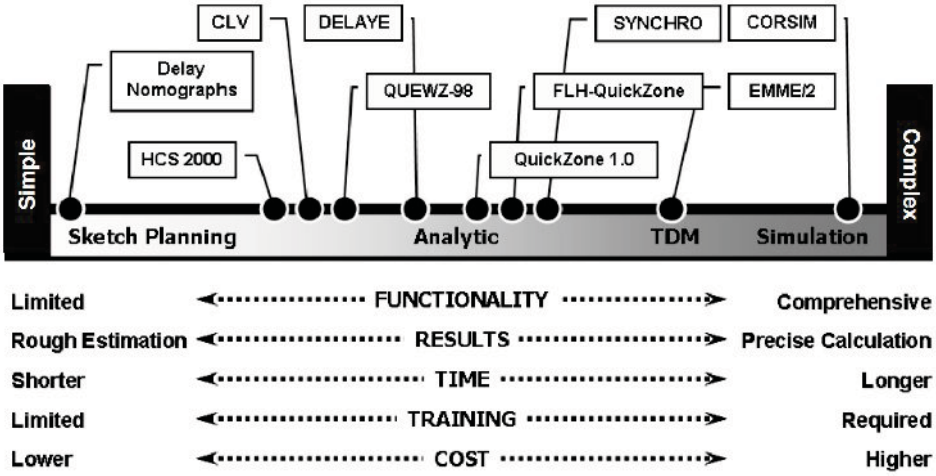

Fig. 1: Work zone modeling spectrum (Hardy et al. 2007)

3.1 Guidance and Manuals

3.1.1 Highway Capacity Manual (HCM)

Methods for capacity calculation are defined in the Highway Capacity Manual (2000). For short-term work zone planning, a simple formula which uses 1600 vehicle per hour per lane (vphpl) as a base number and takes the presence of heavy vehicles, factor for type, intensity, and location of work activity, and on-ramp presence under consideration. For long-term work zone planning, capacity values or ranges are suggested for several specific work zone configurations (e.g. 1550 vphpl for two-to-one lane closure) (Heaslip et al. 2009).

The HCM provides simple rough calculations for work zone capacity estimation. Its accuracy depends on the estimation of input parameters and lacks consideration of factors such as local traffic, geometric, lane width, weather etc. which have great impact on it.

3.2 Multiple Factors Analysis and Decision-Support Models

3.2.1 A Bayesian Belief Network Method

Bayraktar and Hastak (2009) introduced a Bayesian belief network model to analyze the correlated, dynamic factors in an attempt to facilitate the evaluation of highway work contracting strategies. A Bayesian belief network is a directed acyclic graph of nodes, which is a statistical modeling framework using Bayes theorem. It can be used to analyze multiple conditional probabilities. The authors applied three steps to establish a Bayesian belief network model. The first step is to customize the belief network. Fifty two factors are collected under five categories in terms of contract characteristics, motorist issues, public issues, resource issues, and technical issues. All the factors are corresponding to nodes in the acyclic graph of the proposed belief network. Each node has different states, for example state values of rural/semi-urban/urban for the Contract location node. There are four types of nodes, namely Starting, Decision, Intermediate and Target. The Starting nodes accept external inputs for the proposed belief network. The combination of the four Decision nodes, namely lane closure strategy, construction window, work zone length and incentives, represent different contracting strategies. While the intermediate nodes carry the conditional probabilities, the Target nodes represent the outputs of the belief network which are corresponding to the performance indicators. The second step is to define the prior probabilities and conditional probabilities of relationships in the belief network. The third step is to calculate the performance scores of different alternatives by using the output from Step 2. And the performance scores can be used to compare different alternatives.

The authors provide a good analytic method for achieving a balanced contracting strategy. To establish a Bayesian belief network, a huge amount of inputs of probabilities is required. As indicated by the authors, however, there is not a generic way for quantification of the relationships and the estimating of the probabilities is typically based on the model use's experiences. As different people can have different estimation on the probability values, different analysis results might be produced.

3.2.2 A Matrix-based Decision Support Tool

Carson et al. (2008) developed a series of decision support matrices for facilitating decision making in highway construction by investigating literature, case studies, and expert's opinions. By sequentially applying three kinds of matrices in terms of 1) a preliminary strategy selection matrix, 2) more detailed matrices focusing on construction, traffic management, and public information strategies, and 3) an interdependency matrix, practical strategies for highway construction can be obtained.

The matrices serve as knowledge storage. As indicated by the authors, several limitations of this method are identified such as 1) it can only suggest strategies in previous practices, 2) due to the limited number of case studies, it only covers a specific construction type, 3) it lacks the consideration of road user and local residents and business, and 4) it lacks the consideration of construction strategies.

3.3 Deterministic Macro Level Analysis

3.3.1 Linear Programming

In order to solve the traffic closure and work progress issues, Sharma et al. (2009) developed a traffic closure integrated linear schedule (TCILS) method. It generates a single schedule for both the construction work and the traffic closures. As the authors indicate, TCILS is a two-dimensional graphical tool to represent time and space restraints. It is a similar scheduling method as Critical Path Method (CPM) without considering uncertainty and resource interaction.

3.3.2 Construction Congestion Cost (C03) system

Carr (2000) developed a Construction Congestion Cost system (C03) for the Michigan Department of Transportation to facilitate achieving a balance between construction productivity and traffic delay. C03 is implemented in Microsoft Excel consisting of five calculation sheets in terms of routes sheet, input sheet, traffic sheet, construction sheet and impact sheet. Specific values are required as inputs such as capacity for speed delay (V/hr), method travel time (min), diverted cars (%) etc. After the calculation, daily user cost, total user cost and project cost will be produced in the impact sheet.

C03 is a computer aided calculation tool. As the author indicated, the accuracy depends on the input estimates. However, some of the inputs such as the capacity for speed delay, diverting ratio are hard to estimate. And it lacks the consideration of interactions with construction resources.

3.3.3 QuickZone and QUEWZ

Quick Zone (Mitretek 2000; Curtis 2001) and QUEWZs (queue and user cost evaluation of work zones) (Copeland 1998) are two similar well-known deterministic simulation and analytic software tools. QuickZone is a work zone analysis program based on Excel. The closure number and duration of construction schedules of different highway work scenarios need to be entered by users, which is normally base on users' assumptions and experience (Lee et al. 2005b). A similar effort called FLH–QuickZone that was developed by Hardy et al. (2007) focused on accurately predicting queue lengths and delays under two-way, one-lane operations. Due to the simple data input, this kind of software has limited capability to analyze complicated delay situations (Chen et al. 2010). In order to obtain better understanding of construction and traffic operations, microscopic simulation packages are recommended to use by Chen et al. (2010).

3.4 Stochastic Operations Level Simulation

3.4.1 CA4PRS

The Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) was developed by the University of California to facilitate scheduling and production analysis of Long-life Pavement Rehabilitation Strategies (LLPRS) (Lee et al. 2005). It integrates Monte Carlo simulation, critical path method analysis, and linear scheduling to help highway agencies and paving contractors make trade-offs among various factors such as productivity, traffic inconvenience, and agency cost (Lee et al. 2005b). This software takes several factors as inputs, including Rehabilitation type, Construction windows, Lane closure tactics, Material strength-gain properties, PCC (Portland cement concrete) cross-section changes, AC (asphalt concrete) cross-section design, Pavement base structures, Contractor's logistical resource constraints, and scheduling constraints. The optimizing goal is to minimize the total cost which includes agency cost and road user cost. Both deterministic and probabilistic analysis can be performed in CA4PRS. And it has the ability to be integrated with micro- and macroscopic traffic simulation which can help quantify road user costs (Collura et al. 2010).

The output of CA4PRS is the maximum production rate of highway work. Collura et al. (2010) indicated that the analysis of traffic delay and queue length depends on other estimation tools such as QuickZone or QUEWZ. Besides, the collecting of construction related data (such as truck hauling capacities, work efficiencies, pavement properties) for accurate analysis needs resources.

3.4.2 Traffic Control Strategies at Construction Zones

Al-Kaisy and Kerestes (2006) investigated traffic control strategies for single-lane closures on two-lane two-way highways. Four traffic control rules in terms of fixed-time control, fixed-queue control, "static optimum" or convoy rule, and adaptive control have been analyzed by using both deterministic approach and stochastic approach. Variables such as work zone length, average speed at work zone, lost time, traffic level, directional split, and interruptions to traffic by movement of construction vehicles and (or) equipment into and out of the construction site are considered and modeled. While the Webster formulations as a deterministic approach are implemented in Microsoft Excel to calculate the average delay for the first three traffic control rules, it is too complicated to model the fourth rule which involves a number of stochastic factors. Synchro which is signal optimization software and SimTraffic which is considered as the most suitable traffic simulation software for signal operations are adopted in the stochastic approach.

The authors indicated that the highway capacity is critically affected by the construction activity as a result of lane closure. However, due to the limitation of the proposed approach, the stochastic characteristics of the traffic interruption by the construction vehicle and (or) equipment is simplified to a constant value. It is based on two assumptions, namely 1) the access to the activity area is close enough to either end of the construction zone, and 2) construction vehicles can normally get right-of-way at the same time of right-of-way changes between the two directions of travel. Thus, further research on the interaction between traffic operations and construction operations was suggested by the authors.

3.4.3 Asphalt Paving Operations Simulation

Nassar et al. (2003) modeled the asphalt paving operations and the traffic flow on rural two-lane highway using a discrete event simulation method to analyze the interaction between construction and traffic. Variables such as the distance from plant, number and types of trucks, traffic volume, length of lane closure, maximum allowable work zone speed, and lane closure strategies are taken into consideration. The construction simulation method of Stroboscope was adopted to model the detailed paving construction operations such as asphalt mixing, laying down, as well as the transportation of materials. Operations of truck merging into traffic were modeled using the gap acceptance logic. With the proposed simulation model, various scenarios considering the impact of different quantities of trucks, lane opening time, traffic volume, and distance from the asphalt plant were simulated and analyzed, aiming to find a balanced solution between production rate and direct cost.

Due to the limitation of traffic modeling in Stroboscope, only a simplified traffic model is incorporated in comparison with the features in professional traffic simulation software, which might result in inaccuracy analysis of traffic delay and road user cost.

3.4.4 Traffic Arrangement for Microtunneling Operations

Lau and Lu (2010) modeled the microtunneling construction operations and traffic flow using a discrete event simulation method. Microtunneling is a commonly used construction method, which normally requires lane closure for a long period. The simulation model provides capabilities to analyze the following factors in terms of 1) location and size of jacking pit, 2) planning site access, and 3) planning for storage or lay down area near jacking pit.

Similar to the asphalt paving research, traffic behaviors are over simplified in the proposed simulation method. It is incapable to provide sophisticated traffic simulation, thus resulting in rough estimation for traffic-related factors.

4. RESEARCH ON TRAFFIC MODLEING AT WORK ZONE

4.1 Traffic Diversion

Chen et al. (2010) indicated that most work zone impact analysis tools resort to deterministic queuing approaches. In order to overcome the limitations and provide more accurate queuing simulation, the authors combined microsimulation and logistic regression to model the queuing behaviors in work zones with a number of entrance and exit ramps. A diversion module was developed with COM interface in VISSIM. The proposed method produces accurate queue length estimation compared with the field-observation data.

4.2 Capacity Prediction

A great body of research has been conducted on this topic. In order to provide a solid foundation for the traffic analysis at work zones, Heaslip et al. (2009) conducted a work zone capacity research using CORSIM as a microscopic simulation software tool. Variables such as geometric, traffic and work zone parameters were taken into consideration. Three types of work zone configurations in terms of two-to-one, three-to-two, and three-to-one lane closures were modeled. And the simulation results were compared to real-life data and the Highway Capacity Manual 2000. As work zone feature is not directly supported in CORSIM, the incident analysis feature was adopted to imitate work zone behavior. The authors compared the simulation results with the suggested values from HCM 2000 for three-two lane closure. While the HCM suggests a range from 1780 to 2060 vphpl, the proposed method produces more realistic values according to different conditions.

5. Conclusion

The Construction Synthetic Environment (COSYE) developed at the University of Alberta is a .Net implementation of the HLA framework according to HLA standards (AbouRizk 2010). COSYE facilitates integration of different software applications and increases the collaboration of parties on planning and controlling construction projects. Industry applications by implementing COSYE can be found in Taghaddos et al. (2008); Alvanchi et al. (2011); and Azimi et al. (2011).

With CTISIM framework (see Fig. 2) that is developed based on COSYE, Simphony (AbouRizk and Mohammad 2000) is able to communicate with VISSIM (PTV 2011) through the COSYE real time interaction (RTI) server. Simphony that is developed at the University of Alberta is a discrete event simulation platform for construction operations simulation. VISSIM is a well-known microscopic traffic simulation software product that is developed by PTV. They both constitute the construction- transportation simulation federation. All exchangeable data in the federation is defined in the federation object model (FOM) by the object model template (OMT) editor. To make Simphony and VISSIM compatible with the COSYE RTI, communication interfaces are programmed in two modes. For the construction simulation federate, a Simphony COSYE-aware template called RMC template is coded. It is a dynamic link library (DLL) file with the ability to communicate with the COSYE RTI server and can be loaded by Simphony as a special purpose simulation template. For the traffic simulation federate, a VISSIM agent is developed based on the COSYE framework. It invokes the component object model (COM) interface of VISSIM. The logical time between discrete event simulation (Simphony) and continuous simulation (VISSIM) is synchronized in the federation. As such, Simphony and VISSIM are interchangeable and communicable with other equivalent software packages as long as they support a COSYE-compatible interface. The integrated simulation is expected to produce more realistic simulating results by incorporating traffic modeling into construction operations simulation.

As the ready-mix concrete (RMC) is one of the important construction materials for road work and its production and delivery involves both construction and transportation activities, it was adopted as a preliminary case study for demonstrating the feasibility of CTISIM framework. Details of the case study can be found in Zhang et al. (2011). A fully-fledged practical case will be conducted in the near future to account for sufficient granularities in both construction planning and traffic modeling by taking full advantage of the developed CTISIM framework.

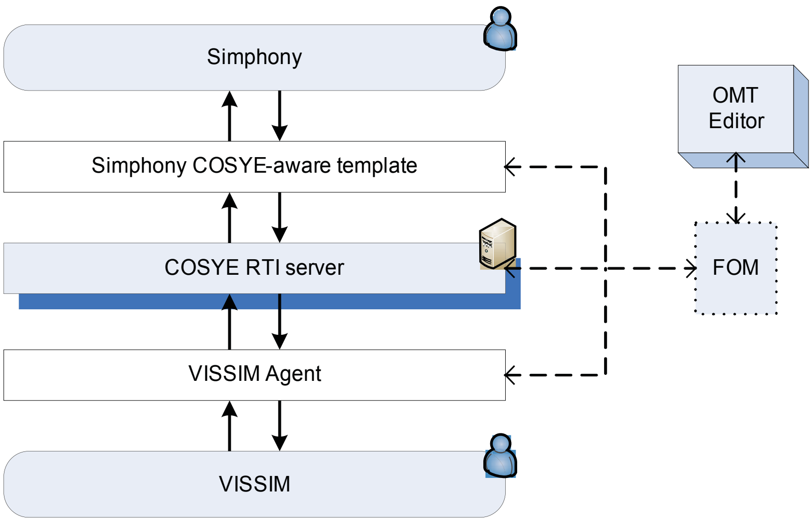

Fig. 2: The Construction-Transportation Integrated Simulation Framework

This paper covers the majority of research efforts on work zone analysis involving construction planning and traffic modeling. It is noteworthy that the decision process on work zone strategies involves deep understanding of the inter-relationships between construction operations and traffic behaviors. However, a comprehensive construction- transportation integrated simulation model which makes the best use of current research findings in construction and traffic respectively has not been developed yet. High Level Architecture (HLA) which is an international standard for distributed simulation has the potential to integrate the two research areas. Thus, a more comprehensive simulation model can be easily achieved.

6. ACKNOWLEDGEMENT

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INFRASTRUCTURE CONCEPTUAL DESIGN IN VIRTUAL 3D ENVIRONMENTS

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ABSTRACT: *Virtual design proposals are becoming an intrinsic tool for ongoing requests for infrastructure change/renewal, to achieve sustainable development objectives, modeling the effects of climate change, and tracking scarce resources. Digital Infrastructure models of different scales are a visual and realistic way of representing the as-is environment and planning ideas in different stages of the infrastructure lifecycle. As 3D modeling becomes more sophisticated, capabilities beyond analytics and clash detection will evolve, resulting in customers and citizens experiencing the change in the world around them before it becomes reality... The design software company Autodesk addresses the conceptual design for infrastructure models in several tools. Let's have a closer look.*

KEYWORDS: *Infrastructure Lifecycle, Conceptual Design, AEC, 3D city modeling, 2D to 3D, Sketching 3d Assets, infrastructure modeling*

1. Conceptual Design for infrastructure models

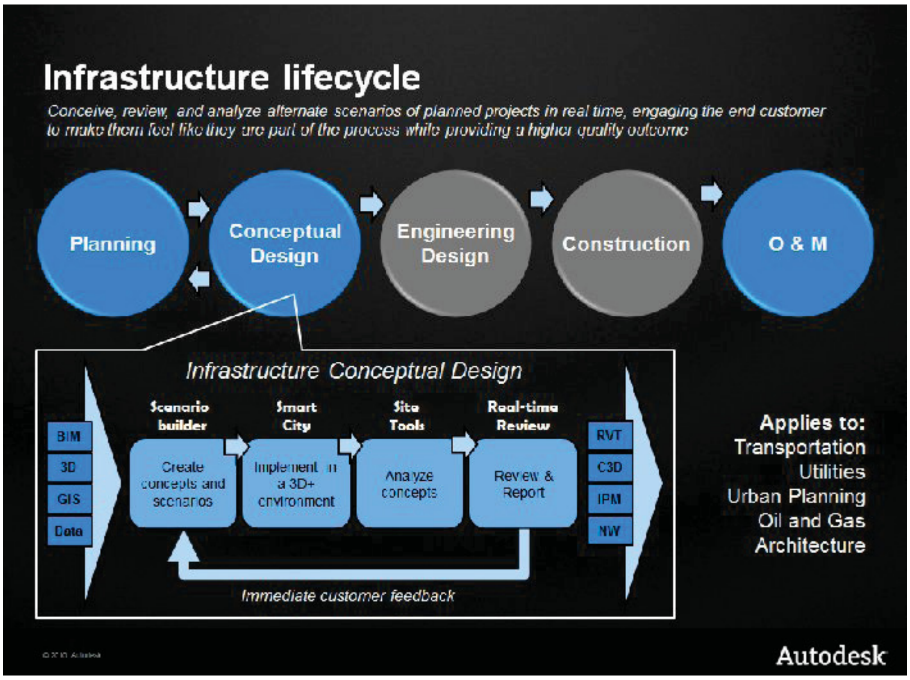

Fig. 1: Infrastructure Lifecycle

Conceptual Design for Infrastructure fits into the planning phase of the infrastructure lifecycle, outlined in the Infrastructure Lifecycle illustration below. To achieve a more efficient process in design and development of new infrastructure (project sites, street segments, bridges, landscape, wind parks, etc.), an infrastructure design tool helps visualizing the idea and shaping a clear picture in the minds of all participants. Better evaluation and acceptance when entering the engineering design phase results from visualizing the project. As seen in the graphic below, the conceptual design phase may be repeated as needed to collect as much feedback as possible, and to incorporate feedback in order prove the concept. Taking these steps helps avoid increasing costs and delays later in the project.

These insights came from feedback from the community, talks, and surveys within the AEC world. In the past 3D has been an integral component in the planning and conceptual design of infrastructure construction and redevelopment projects: designers published their ideas to customers, stakeholders and decision-makers by using wood, clay, foam, paper, and photo manipulation to transfer their ideas and feeling for the layout of new roads, railways, and building development.

Starting recently with BIM for Architects and Engineers, following with 3D for Civil Infrastructure and rising 3D city models from 2D GIS data, the market now searches for:

- 3D workflows for planning
- Integration of GIS & BIM
- Visualization of large infrastructure projects

Customers need to combine geospatial and design models (CAD, GIS, BIM) into a cohesive infrastructure solution that allows them to sketch and visualize in large contexts, analyze and share conceptual designs, plans and proposals. Infrastructure solutions show real world context, change over time, as well as comparing and contrasting multiple versions of a design.

Cities have grown over the past centuries and now need to adjust their infrastructure to meet new, increasing demands. New requirements also arise from achieving sustainability objectives, by changing population structures and by considering resource saving aspects more seriously. Decisions have to be communicated in a persistent way throughout the different planning stages beginning in a first conceptual design based on a 3D virtual environment.

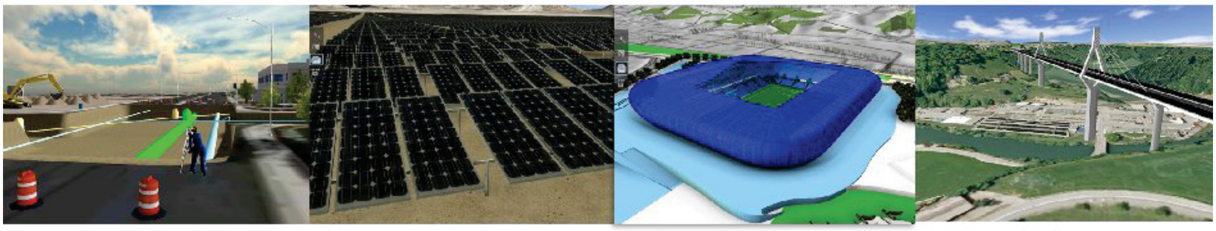

Image Courtesy of VTN Consulting - Las Vegas, USA *...of City of Le Havre, France* *...City/State of Fribourg, France*

Fig. 2: Samples of Conceptual Design

Decision making on top of different proposals has always been a matter of communication, presentation and imagination of people involved in the process. Planers, Engineers, Stakeholders and the Public are looking differently at 2D proposals and produce their own ideas of "what could be". Basic changes to a plan can be sketched and presented in a 2D environment. This is the way most planning authorities work. When it comes to complex proposals within an infrastructure model a 2D representation cannot create a fast and similar understanding of an initial idea.

Architects often present their work throughout high rendered imageries. This situation is framing the need for a more realistic view of planned infrastructure. Often their clients aren't able to read CAD drawings in the same way professionals would do. By using virtual realities starting in the conceptual design phase those architects are able to win more work or project approval by presenting design proposals within the existing as-is 3D environment. To place a design intent into its real context, e.g. in an infrastructure model, all participants are gathering mostly the same look and feel how this design might fit and throughout the simple navigation first evaluations can be made side by side with the architects. Another benefit of bringing the design proposal into the model is the comparison between different designs. This is a lot easier than simply reviewing different renderings from different angles in different environments.

One need in conceptual design is that AEC (Architects, Engineering, Construction) firms, GIS experts and Planners want to be able to sketch assets not only in plain 2D much more they would like to see a realistic 3D presentation of their planned proposals right away, avoiding extensive renderings. They need to be able to sketch new designs digitally in 3D, and create and manage different design proposals in one model.

More and more Civil, BIM and GIS professionals are using 3D technology to communicate projects, design proposals to clients, stakeholders or the public. One thing missing is the context. The virtual 3D environment can provide information and analytics to verify design alternatives in a very early stage of the planning process. This allows a faster, more confident decision making and greater stakeholder buy-in towards a sustainable infrastructure design. After a proposal has come to reality, all the different information - Civil, BIM and GIS -can be used to update the "what is" infrastructure model and be used for new demands in planning, analyzing and representing future "what could be" scenarios.

For planners and engineers involved in infrastructure planning, an infrastructure modeling application helps to communicate 'What could be' in the context of 'What's Already There.'

The 3 subjects being presented today are:

- Quickly and Easily Creating Conceptual Designs for Infrastructure Proposals
- Creating a Context Model Representing the Existing Natural and Built Environment
- A Visually Rich Experience for project stakeholders

People are visual animals. They understand pictures better than words and a visually compelling 3D model helps to make better informed decisions, win work, and gain stakeholder buy-in.

In summary, an application helps planners and engineers to gain faster project approvals by creating and visualizing infrastructure project proposals in the context of the built and natural environment.

Virtual Realities aren't nice renderings anymore; they are enriched by typology, attributes, connectivity information, etc. and supported by tools for a faster visualization of ideas, plans and concepts. Demoing this application already proves that the idea is right in the heart of AEC and that GIS users are very pleased to have an approach of entering right in the VR instead of creating base dataset to turn them into 3D assets afterwards. The wish of having something like a 3D GIS has not come true yet, but getting BIM, Civil and GIS data combined within a infrastructure project throughout a seamless workflow makes work and decisions much more confident and sustainable based on compelling virtual realities.

BIM – HISTORY AND TRENDS

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ABSTRACT: *This paper examines the history and the components of Building Information Modeling (BIM) in the context of the industry and market dynamics. We discuss the key technologies and their chronology to explain the inception of BIM. We identify the dual role of BIM as practical tool and idealized concept. As a tool, BIM is responsible for many documented Architectural, Engineering and Construction industry (AEC) achievements. We emphasize its importance in setting the direction toward computer-aided collaborative environments and integrated workflows. As a concept, BIM symbolizes the AEC activity, and stimulates a discourse about the architectural profession and its future. It engages both the academic community and professionals and provides a converging point for their perspectives. We use this concept for theorizing the future capabilities and limitations of BIM. BIM is a symbol of collaboration yet the adversarial nature of corporate branding and market domination has resulted in many mutually incompatible BIM offerings. BIM inherits from CAD's paradigm of numerical precision. Consequently, it interfaces poorly with early ideation stages. We propose that the continuing progress in computing technologies is driving the trend toward complex, highly integrated tools and workflows. In this context, BIM has the potential to expand along, and across, workflows and processes. We examine the internal and external weaknesses of BIM, and discuss the possible directions of BIM evolution. We conclude that the unique contribution of BIM lies in establishing the milestone and the direction for the AEC industry. BIM's inception has oriented the AEC industry toward becoming the media of regional and global collaboration in planning and developing built environments.*

KEYWORDS: *Building Information Modeling, BIM, AEC, architecture, construction, collaboration, workflow.*

1. Introduction

In this paper, we adopt a factual approach while tracing the development of BIM. The chronology of technological milestones and the dynamics of market decisions bring out the image of BIM as a collection of disparate marketing strategies rather than a universal AEC language. Nevertheless, the concept of BIM as the tool of collaboration across teams and across workflows is strongly established. We use this concept in an abstract and idealized sense to theorize potential directions of BIM's future development. We explore a hypothetical scenario where the nucleus defined by the current BIM expands constantly across related activities, workflows, processes and into the future. Through these transformations, we probe the concept of BIM and its potential.

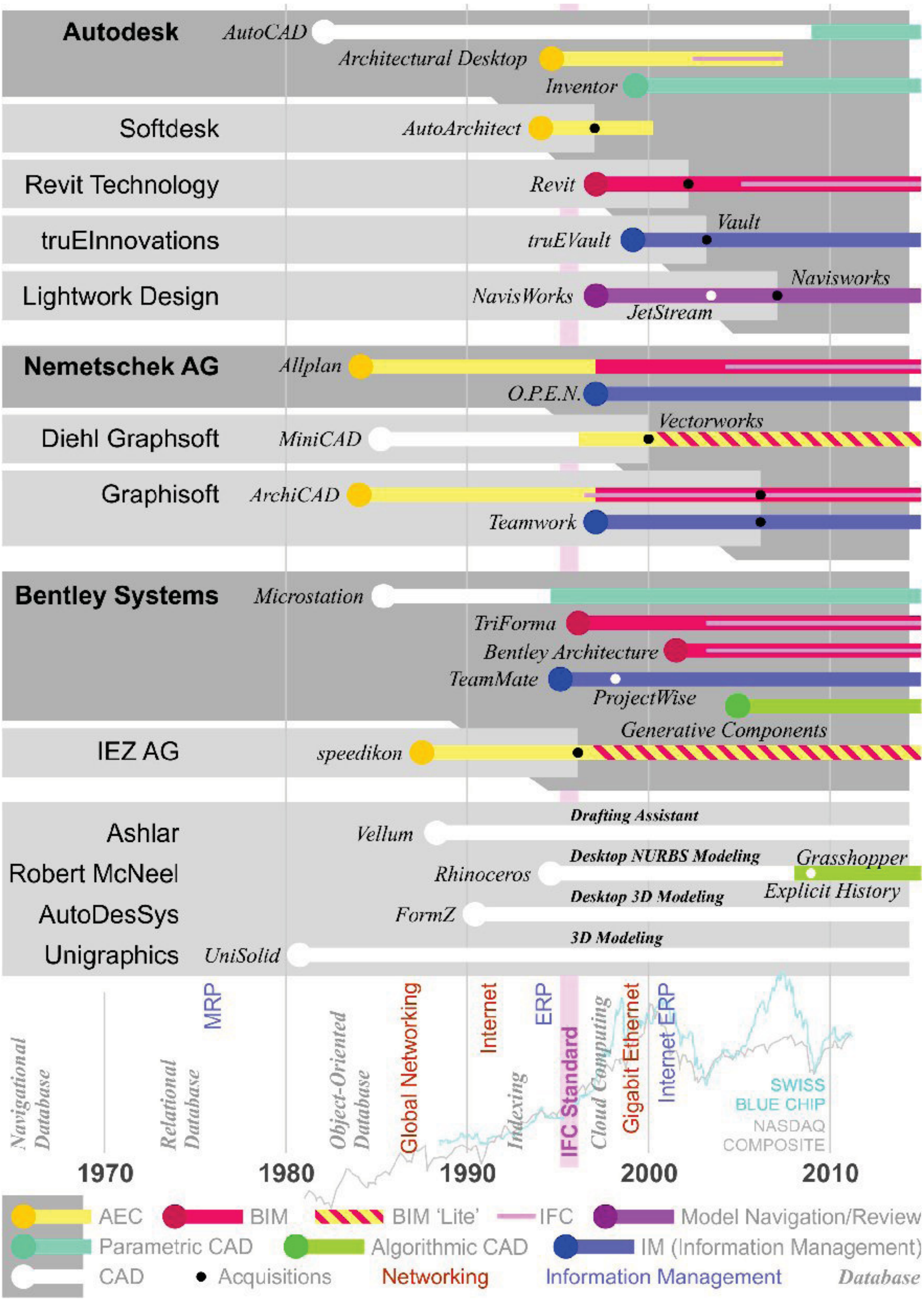

Fig. 1: Technology and chronology. (Wierzbicki 2011)

2. Chronology

Figure 1, maps the timeline of software technologies over the context of market activity. The key industry players followed different strategies. Some relied on their traditional main CAD platforms and built BIM solutions around them (Bentley, Nemetschek). Others developed entirely new modeling engines (Autodesk). In all cases, a complex blend of CAD and AEC technologies established the foundation of 3d parametric modeling. Once integrated with an Information Management system of choice, it becomes the final BIM solution. IM technologies took off in late 1990s.

In the same period, CAD, and AEC, became universally parametric. AEC and IM were integrated and became BIM. This vigorous software development activity coincided with many decades long period of exponential economic growth that continued until 2001. Afterwards, the technology development tended to be limited to incremental improvements. The market activity focused rather on acquisitions. One of such acquisitions ended the independence of the major BIM software pioneer – Graphisoft.

3. Technologies of Collaboration and Process

Researchers agree that collaboration is essential to BIM. This collaboration expands in two directions. First, BIM is a CAD interoperability tool that links together design models and files of all AEC disciplines. Second, BIM is an Information Management platform that enables the synchronous co-operation between, as well as within, all involved teams. Although CAD interoperability is three decades old and it is supported by standardized data exchange formats like SAT, STEP, or IGES, it provides mostly a non-associative, one-way translation. BIM is more demanding as it relies on two-way, interactive and on-the-fly coordination of parametric data. Nevertheless, such expanded functionality of data exchange is an incremental improvement rather than a technological breakthrough.

In contrast, collaborative team environments are a fairly new technology that was pioneered by projects like TeamMate, Teamwork, O.P.E.N., truEVault and NavisWorks during the second half of 1990s thus coinciding with the development of Enterprise Resource Planning (ERP) tools, which integrated information flow across entire organizations. Furthermore, all these new collaboration tools needed to rely on the newest networking technologies like Internet and Gigabit Ethernet. The emergence of collaborative technologies marks the tentative inception of BIM as all major developers have immediately integrated their collaboration tools with their respective AEC packages. By that time, 3d modeling was already universally parametric.

Notable are the different strategies adapted by the major industry players. Bentley and Nemetschek base their products on their main CAD platforms that are being continuously developed. Autodesk tries a few approaches before adapting and combining new CAD technologies. Bentley and Nemetschek diversify their market offerings by acquiring other AEC/BIM platforms. Such variety of strategies and components highlights the fact that the BIM's touted integration, interoperability and collaboration are a delicate compromise of very different technologies (Neff, Fiore-Silfvast 2010). In all cases, the 3d modeling is the underpinning of the final product. However, even this core component is a varying mix of surface and solid modeling methods.

Is BIM a process? Although this term is frequently associated with BIM, it may be rather the result of an idealized projection rather than actual attributes. Scholars define a process as a sequence of actions aimed at transforming inputs into a desired outcome. Other, and related, attributes of a process are 'decision,' 'purpose,' 'learning,' 'expertise' and 'quality.' Furthermore, the term process has a wide application scope ranging from industrial automation to entire business organizations. In all cases, the process is temporal in nature and involves sequences of actions. A tool can be considered as a low-level component of a process. A tool may imply some logical steps of a process. Yet just by itself, it does not reveal anything about its goal, expertise or decision. Only within the context of a process, the tool can play a meaningful role in defining such attributes. In its current form, BIM exhibits more properties of a tool. Nevertheless, this raises questions whether BIM can become a process, what would be needed to accomplish this and whether there is a good reason to pursue such expanded function of BIM (Ottchen 2009).

Also coinciding with the inception of BIM, Business Process Modeling (BPM) became the subject of vigorous activity on theoretical and practical applications levels. Emergence of BPM software developers like SIMUL8, Metastorm and CreateASoft coincided with the insurgence of Information Management (IM) technologies. Coupling BIM to BPM would create a system capable of governing all activities in an organization. Yet, it is important to identify the conceptual differences between BIM and BPM. BIM needs to remain as a relatively open-ended and transparent production tool in order to handle a broad range of architectural projects. BPM, once implemented, becomes a unique and relatively permanent expression of organization's policies on efficiency, quality, purpose and ethics. As such, BPM may adapt a supervisory role and monitor the efficiency of project delivery, administer project management details like human resources assignment and track the quality of communications between team members, teams and external parties.

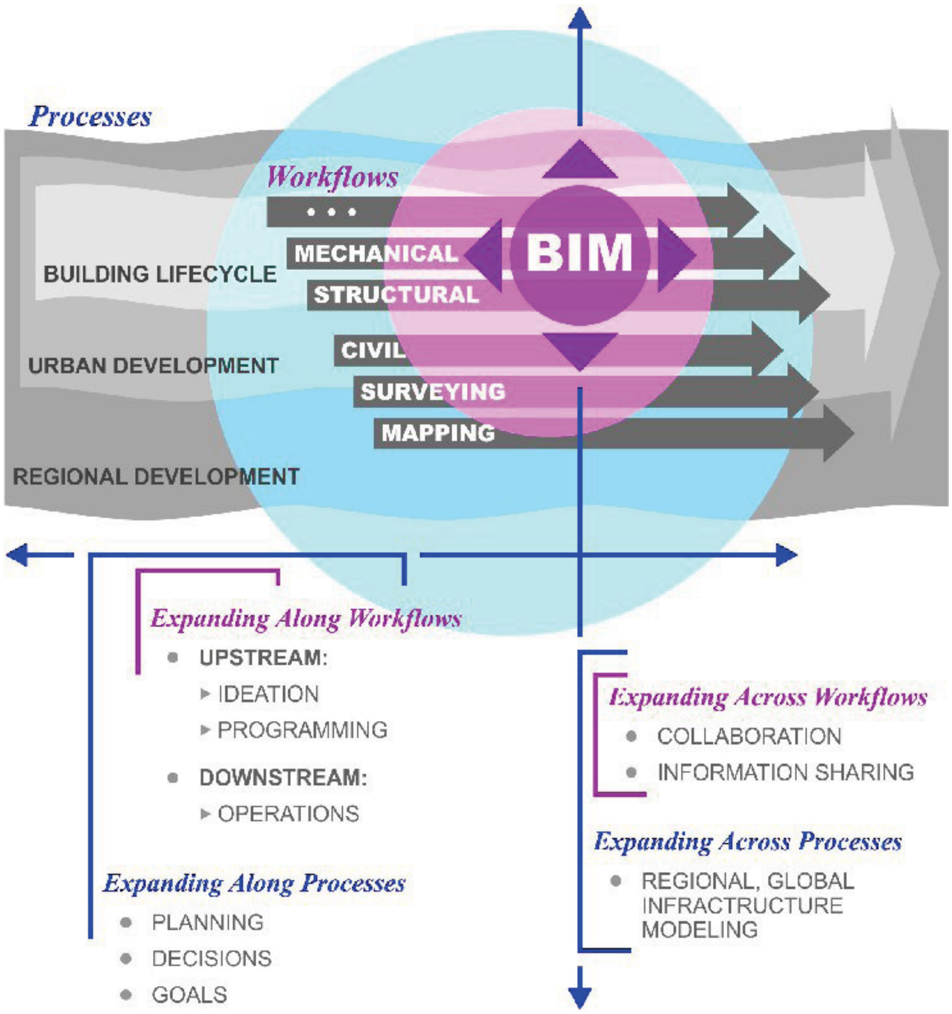

Fig. 2: Trends.

4. Trends

BIM, as a fusion of CAD, information management, and collaboration technologies, extends over various building delivery workflows: architectural, structural, electrical and HVAC. We identify and discuss two directions of this extension. BIM spans across the workflows by providing a platform for collaboration and information sharing. The other axis is along the workflows, or, as researchers often refers to it, upstream and downstream.

Along this axis, BIM provides support for various phases of workflows: initial design, detailing, design verification and construction documentation. Furthermore, we theorize, along these axes, the trends and the potential of the future BIM evolution. The Figure 2 maps BIM's expansion over a backdrop of workflows and processes related, technically and administratively, to building construction.

The 'across' direction spans over civil engineering and GIS. In fact, BIM-GIS integration is currently very active (Laat 2010). This direction points toward the 'macro' scale of BIM's scope: through urban and regional to global infrastructure modeling. There is also the potential for BIM to expand in the 'micro' direction (not shown on the diagram). Such direction would link BIM to material engineering thus enabling access to the newest materials as well as driving the demand for new materials. The engineering side would benefit from systemic data collection from actual buildings. Another extension toward the 'micro' end would be integration with social sciences. Buildings play the critical role as behavioral settings. Ubiquitous information technologies expose designers to immense amounts of data Ottchen 2009). Designers would be able to incorporate perceptual criteria and employ behavioral analysis tools. Researchers would gain access to behavioral data collected from actual settings. Urban areas are subject to increasing level of surveillance. Scholars note the inevitability of such approach in view of the increasing urban density. They also point out the evolving paradigm of surveillance, the notion of participatory surveillance and the role of ubiquitous connectivity. In all, surveillance needs not to be exclusively derogatory measure. Instead, it can also become a tool of emotional comfort management.

Within the limits of workflows, the 'along' axis is the subject of considerable body of research. Scholars conclude that, at this moment, BIM is weak in supporting the 'upstream' direction: early design stages and ideation (Eastman 2008, Penttilä 2007, 2009). Also, the 'downstream' direction that supports the post-construction operations needs much improvement. This indicates that BIM has not evolved yet too far from its CAD underpinnings. Workflow stages that rely on non-CAD approach tend to be poorly supported by BIM (Sturts 2010). Researchers point out that BIM needs to develop the capacity of dealing with 'soft' qualitative data in order to support early design stages. This implies a significant leap beyond the limitations of CAD's explicit numerical modeling. Also, the operational 'downstream' requires different data structures that are suitable for managing temporal variability. In contrast, CAD relies on modal representations – numerical 3d models do not 'age,' meaning there is no natural temporal component in them.

The outer circle indicates the expansion beyond the 'productivity' workflows and into the domain of higher-level governing processes. Comprehensive building lifecycles, urban and regional development establish a large-scale temporal arena for potential BIM activities. When directed toward the future, BIM has the potential to become a tool for planning, decision-making and goal development. In this capacity, indispensable will also be the access to the past. An easily accessible repository of historical records will be the source for analysis and knowledge making. If expanded over such large geographical and temporal scales, BIM gains the potential of becoming a tool of governance, perhaps even global governance.

4.1 The role

Achieving efficiency in integrated workflows relies on eliminating duplicate and non-contributing (non value-added) tasks as well as process bottlenecks. This exposes the traditional workflows to a scrutiny, which, in its procedural and unemotional pursuit of productivity, often questions the established wisdom and habits. For instance, whether BIM empowers architects, or rather, whether it diminishes their role. Whether it streamlines the job of engineers to the point where the concept-to-construction workflow becomes a viable option. Such questions flex the boundaries of the traditional professions and facilitate the discourse on their future. Here, BIM becomes the catalyst of change, the source of new capabilities and the target of new skills. BIM affords this pivotal position of importance thanks to its tremendous potential as a project delivery tool (Pniewski 2011). The AEC industry quotes examples of BIM's contributions in terms of efficiency and cost reduction. Nevertheless, it is important to point out that BIM is far from becoming a universal remedy to AEC ailments. Thus further confirming its role as a complex and potent, but merely a tool, its success depends on the intersection of its functionality and the operational processes of an organization. Therefore, a skillful fusion of technology (BIM) and process (the organization) is the necessary yet elusive and difficult to quantify step. Architectural projects are complex and notoriously diverse thus further complicating matters. An efficient delivery of one project does not necessarily assure the same on a different one. This opens yet another debate: whether BIM is the vehicle of typification, or whether it enables uniqueness and customization.

4.2 Evolution

The question is if or when BIM, while undergoing this hypothetical expansion, becomes sufficiently detached from its original purpose and starts loosing meaning within the new context. This opens the exploration of semantic evolution of BIM. Although, if assuming a gradual and continuous expansion, we can trace at any stage a logical connection between the new and the old, the phrase Building Information Modeling may become misplaced. For such comprehensive and vast information structures the identifier 'Building' would probably yield to a term reflecting better the 'total' and 'global' aspects.

Many researchers have noted the BIM limitations that are stemming from its CAD origins. What are then the possibilities of expanding its scope? As BIM is the result of one strong technology (CAD) becoming an attractor and a binding nucleus for many supporting satellite technologies, a new strong technology transcending the current limitations may form an entirely different nucleus and assimilate BIM in the process. Although speculative, such scenario has a few plausible candidates. Strong Artificial Intelligence is a machine-based intelligence that equals or surpasses that of a human. Synthetic Intelligence is a hypothetical concept of intelligence that is entirely different from that of a human. A machine-based knowledge-making and reasoning entity would open unprecedented possibilities. It would also pose unprecedented problems – researchers' caution. Nevertheless, it would be capable of integrating the entire BIM and use it as a task-oriented effector.

Yet another test of BIM's resilience during these hypothetical transformations relates to the 3d modeling capacity. What are the limits of usefulness of a numerical 3d representation? The entire globe can be represented as such model. This is a viable option using, for instance, cloud computing. However, other complementing global characteristics require different methods. The already developed and in use Global Climate Model technology is based on Computational Fluid Dynamics. Modeling social activity relies on motion, locational indexing and agent-based programming rather than 3d detailing. On the global scale, a 3d model becomes one of many components of equal importance.

4.3 Limitations

Although the general notion of BIM is that of a tightly integrated and coherent system, researchers note many issues originating from the structure of BIM itself. The process of designing is an iterative temporal activity while a 3d parametric construct is inherently modal (Shelden 2009). Reconciling these disparities involves always a work-around in the form of versioning, document and file management using database tools. In the process, the integrity of the 3d model is altered by adding an abstract dimension of changes and versions. Only a rigorous control by the supervisory database logic assures a coherent representation across all AEC threads.

Collaboration is the important declaration of BIM. However, it is noted that the mere existence of many brands of BIM has raised challenges. The IFC data exchange standard is aimed at providing a consistent framework for information exchange between various BIM. Researchers point out though the limiting effect of the common (lowest) denominator. The chronology also reveals an interesting disparity between the focus of major developers on intra-BIM and inter-BIM collaboration. Four different collaboration solutions have been integrated with four different CAD platforms in less than three years – BIM is born. In contrast, adapting the IFC standard spans nine years.

5. Conclusion

The image of BIM is complex and bears signs of being an answer to the wishes of practitioners as much as being the result of a marketing strategy. Besides being a tangible tool responsible for many documented AEC achievements, BIM plays an important role as an abstract concept of architectural activity. As such, it provides a far more resilient ideal of collaboration and integrated workflow than its practical incarnation. It transcends the boundaries of current professions and workflows. It engages the academic community in an explorative discourse about the future of the AEC industry and the architectural profession. We sourced from this inspiration to examine the potential of BIM's future directions of development. Regardless of whether it will remain as such, whether it will be assimilated by other technologies, or whether it will disintegrate from within, BIM has already established an important milestone, laid out the direction toward collaborative environments, and integrated workflows. BIM has formed the nucleus of significant development potential for the future architectural workflows.

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AUTOMATED GENERATION OF STRUCTURAL SOLUTIONS BASED ON SPATIAL DESIGNS TO SERVE AS A SUPPORT TOOL IN EARLY STAGES OF THE DESIGN PROCESS

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ABSTRACT: *Design processes are sets of complex, iterative and multidisciplinary procedures applied to achieve particular solutions. To aid in the understanding of design processes and to support the involved actors, a "Research Engine" (RE) is being developed. The RE is a set of computational processes which work together, in a cyclic manner, to simulate the interaction between spatial designs instances and structural solutions within a design process. This paper presents the first developed phase of the RE; in which the Spatial Design is transformed into a Structural Solution. In other words, given an orthogonal geometry (Spatial Design) this process generates a structure, performs a structural analysis and, consequently, provides an indication of its structural behavior. In early stages of the design process, this phase of the RE could help designers to (1) devise different structural solutions for a given spatial design; (2) to obtain an indication of the spatial consequences of the structural solution; and (3) to predict the structural behavior of the generated solution. Examples illustrate the process in practice during this first phase of the RE, and also show its capabilities in assisting in the integration between spatial and structural considerations within the design process.*

KEYWORDS: *Spatial Design, Structural Design, Pattern Recognition, Transformation Rules, FEM.*

1. Introduction

Design is a multidisciplinary task in which designers and engineers work together on the same problem to come up with feasible solutions. The final solution is usually the result of an iterative and cyclic process, in which the original design undergoes several changes and adaptations to meet pre-defined requirements. Several research projects have been carried out to study these intricate processes and to develop computational tools to improve the outcome of the processes (Fenves et al. 1994; Rosenman et al. 2005).

In the area of Architecture, Engineering and Construction, computational tools have revolutionized not only the manner in which spatial (architectonic) designs are generated, but they have also changed how structural engineers tackle everyday problems. Structural support software is of two types: (1) structural design tools and (2) structural analysis and optimization tools (Coenders and Wagemans 2005). While structural analysis software is intended to generate precise information regarding structural performance and behavior, structural design tools focus on the spatial consequences of a given structure (Holzer et al. 2007).

However computational tools that support conceptual structural design are not yet sufficient; since they do not recognize differences between spatial and structural design processes (Mora et al. 2008). The currently available software which support spatial and structural design processes is focused on and limited to specific tasks concerning their own discipline; geometry generation for spatial design processes and structural analysis and optimization for structural design processes. Moreover, the software does not promote the integration of both disciplines or the exchange of information between processes (Malkawi 2004). Designers and structural engineers are inherently different. Although they work together to address common problems, they have different concerns, they try to fulfill different purposes and meet different requirements, and they measure their success according to different scales (Peters 1991).

All these reasons are partially responsible for the lack of integration between the disciplines within the design process. The most significant differences concern the difference in nature, grounds and purposes of both design processes. However, the absence of structural considerations in early spatial design stages greatly affects the final outcome. By considering structural matters early in the design process, a more integrated design is usually achieved, and both structural and spatial requirements are fulfilled.

The goal of the project presented in this paper is to develop a computational tool which simulates the interaction between spatial and structural design processes, in order to: (1) study the influence of transformation methods on the design instances; (2) to study the influence of transformations on the design process; (3) to find optimal spatial and structural design instances; and (4) to serve as design support tool, providing useful information on the design's structural behavior, in early stages of the design process.

The approach is to develop a so-called "Research Engine" (RE) that simulates an iterative design process. The RE should be able to recognize a spatial design (inputted by the user), then propose a structural solution for the given design, optimize the structure, and finally propose changes to the original spatial design. All these processes are carried out in a cyclic manner.

However, in reality design processes are much more complicated than suggested above, and are not only subject to structural considerations. The RE will not pretend to reproduce the actual process carried out by a team of experts nor its outcome, but to give academic insight into the design process and to serve as a support tool for the exploration of structural solutions and decision making.

This paper briefly explains the whole RE and gives a detailed description of its first phase: the proposal of a structural solution, and the prediction of its structural behavior, based on a given spatial design.

2. Research Engine

The RE simulates iterative design processes and describes interactions between spatial and structural considerations. It is composed of four processes or phases which mimic the interaction between structure and space: (1) Spatial Design to Structural Solution; (2) Structural Solution to Optimized Structure; (3) Optimized Structure to New Spatial Design; and (4) New Spatial Design to Optimized Spatial Design. These four processes compose a cycle (Figure 1a, 1b) which is repeated as often as necessary to meet the user's requirements. The first process has been developed and implemented successfully, and is presented in this paper. The other three processes will be developed in the near future; a brief description is presented in this section. Note that the specific transformation processes, whether already developed or planned, do fulfill the previously stated goals. However, they are not in any way unique and could, in the future, be replaced by others to further improve the understanding of design processes.

(a) (b)

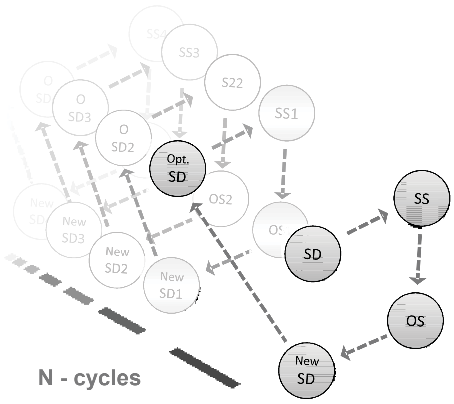

Fig. 1: Research Engine

2.1 Spatial Design to Structural Solution

The first process carried out by the RE is to generate a structural solution from a spatial design; followed by a structural analysis. Several methods exist which transform a spatial design into a structure that later can be analyzed by structural design software (Rafiq and MacLeod 1988). In this process, a method known as "zoning" is used to produce "structural zones" (elemental structural entities) based on sets of "rooms" (elemental spatial entities) inputted by the user. Subsequently, a structure is generated and a FEM (Finite Element Method) structural analysis is performed. This phase of the RE has already been developed and is further explained in Section 3.

2.2 Structural Solution to Optimized Structure

Having generated a structural solution, the next step is to improve its structural behavior. Structural optimization (Bletzinger et al. 2005) and form-finding (Mei and Wang 2004) are two different approaches to transform existing structures into new improved ones. Structural optimization consists of finding optimum values for the variable properties of a structure in a specific load situation. Form-finding, on the other hand, relocates the position of the structural elements' mass so as to improve the load's flow throughout the structure. A variant of form-finding (Rots 2005) could be used in this process. While in form-finding the mass which is subject to low strain levels is relocated, in this process is deleted. This could be achieved by removing those structural elements that do not carry considerable loads.

2.3 Optimized Structure to New Spatial Design

Transforming a structural solution into a spatial design is a process usually carried out subconsciously by designers. Hardly any scientific research has been done in this area (Fenves et al. 2002; Mora et al. 2006). A structure is an arrangement, of different types, of structural elements combined together to create or to delimit a specific space. The geometric properties of the structural elements and its position in space are easy to understand; but to identify the spatial consequences of the whole arrangement is much more difficult and complex. If it is possible to generate a structural solution from a spatial design, then it must be possible to derive a spatial design from an existing structure. The method, which could be followed here, uses the nodes of the structural elements to find and re-generate zones with a technique equivalent to the one presented in section 3.2.1 (Zoning).

2.4 New Spatial Design to Optimized Spatial Design

In this process, the newly generated spatial design is optimized. Several criteria could be used as parameters to improve the New Spatial Design; these criteria should be based on spatial and architectonic concerns. For instance, this optimization process could resize all the newly generated zones, such that the volume of the inputted spatial design and the generated spatial design are the same. In this way, the outcome of the process would be a different spatial design than the inputted one, but with the same spatial capacity. The Optimized Spatial Design is then re-inputted in the RE and a new cycle is started (Figure 1b).

3. Spatial Design to Structural Solution

This section presents the first developed phase of the RE. In this stage, the RE generates a structural solution based on the inputted spatial design. The transformation process carried out in this phase consists of intermediate models (Figure 2) and several procedures (Figure 3). Both are briefly described in this section.

3.1 Models

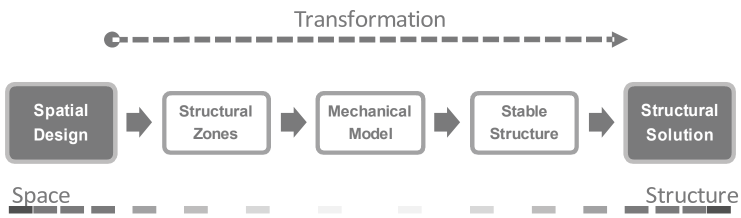

Fig. 2: Models of the Spatial Design to Structural Solution process

3.1.1 Spatial Design [Input Model]

The Input Model or Spatial Design is defined by the user. The tool is restricted to work with right cuboids, parallelepipeds bounded by six rectangular faces, so that each adjacent face meets at a right angle. The right cuboids or "rooms" should be aligned with the global coordinate system. The user determines the three dimensions of the room and its position in space.

3.1.2 Structural Zones

This model is a set of right cuboids, termed structural zones, which are generated by grouping adjacent rooms from the Input Model. Several feasible arrangements can be generated depending on the user's demands. For example, a few large structural zones can be created by grouping various rooms together or many small structural zones by clustering few rooms. The composition of this model will have a big influence on the end result; a structural zone is an elementary structural preposition which determines where and how structural elements are placed to form a complete structural solution.

3.1.3 Mechanical Model

This model consists of structural elements: columns, beams and flat shells. Each structural zone is "structured" or constructed by a combination of these elements. The mechanical and geometrical properties of the elements are predefined by the user.

3.1.4 Stable Structure

The Stable Structure model is essentially the same as the Mechanical Model presented above, but some geometry (structural elements) and constraints are added to the model to achieve kinematic determinacy. As such, this mechanical model allows a FEM structural analysis to be performed.

3.1.5 Structural Solution [Output Model]

The output model is a representation of the structural behavior of the proposed structural solution. This model contains data about predicted displacements, strains and stresses and will be the starting point of the structural optimization process.

3.2 Procedures

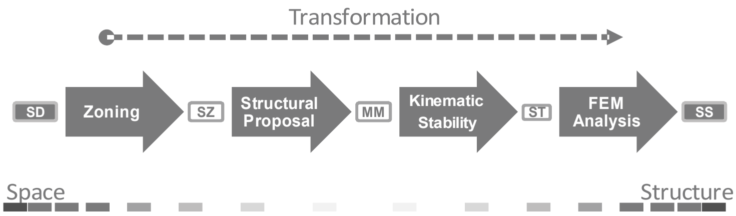

Fig. 3: Models of the Spatial Design to Structural Solution process

3.2.1 Zoning

Pattern recognition algorithms are used within this procedure to find - in the Spatial Design model - all existent corner nodes. All possible structural zones are generated and then grouped together to form useful combinations (Figure 4). This is a fully automated three-dimensional approach which has shown effective results. Existing approaches, namely automated two-dimensional and manual selection, are unable to find all possible structural zones combinations (Hofmeyer and Bakker 2008).

This procedure first locates all the corner nodes of the inputted spatial design rooms, and then finds all possible node combinations that could generate right cuboids (structural zones). However, this method will quickly lead to a combinatorial explosion of possibilities, even for a small number of corner points. To avoid this problem, a Geometrical Related Reducer (GRR) is defined. The GRR is a user-defined filter, which finds zones according to specific geometrical requirements.

The next step is to find all the possible sets of combinations of the founded structural zones. The same problem, as in the previous step, arises here. Investigating all possible set of combinations of structural zones will result in a very long search time. Therefore another user-defined filter is used, namely a Matrix Coupler (MC). This filter determines if one structural zone can be combined with another; for example, to avoid empty structural zones or repeated sets of structural zones. This method generates a collection of useful combinations, which can be backtracked in real-time, so the user can choose the preferred combination.

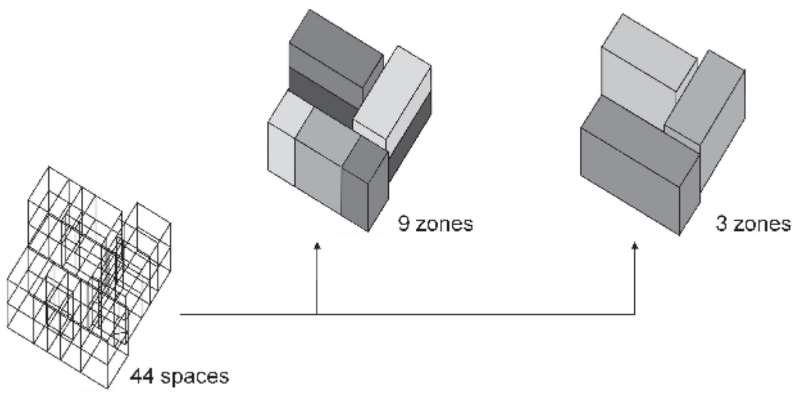

Fig. 4: Example of the Zoning Procedure (Hofmeyer and Bakker 2008)

3.2.2 Structural Proposition

The generated combination of structural zones now serves as a base on which to place structural elements (columns, beams or flat shells) and to generate a structural solution. The manner in which these structural elements are combined and placed is determined by the so-called Spatial-Structural Transformation Rules. These rules are partly inspired by shape grammars (Kotsopoulos 2006), structural grammars and parametric templates (Sacks et al. 2000). This procedure determines which structural element is selected and where it is to be placed, depending on the geometrical properties of the structural zones. Examples of two of these rules are shown in Figure 5.

Note that the geometrical and mechanical properties (e.g. dimensions, Young's modulus, Poisson's ratio, etc), of the placed structural elements, are defined during this stage of the process; so that they can be used later on during the FEM Structural Analysis.

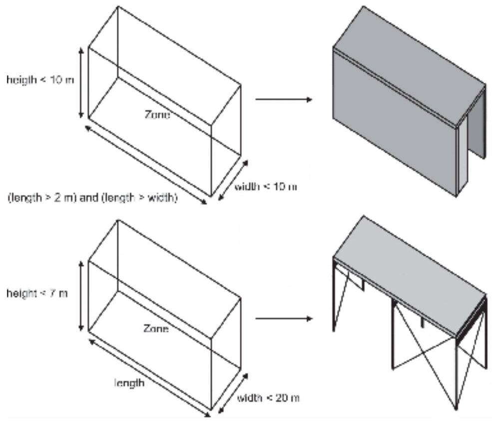

Fig. 5: Example of Spatial-Structural Transformation Rules (Hofmeyer and Bakker 2008)

3.2.3 Kinematic Stabilization Procedure

In order to perform a static structural analysis a kinematically determined structure is needed. However, it is very unlikely that the resultant structure from the previous process will be kinematically determined; this procedure generates such structures. Kinematically undetermined structures are those with insufficient number of constraints therefore mechanisms can occur. Mechanisms are parts of a structural system that could freely move with respect to other parts (Figure 6).

This procedure first generates a Finite Element model to calculate the null space of the structural stiffness matrix, which is a set of null vectors. These null vectors represent a unique mechanism: they list the nodes which can move freely and indicate in which direction the nodes can move. With this information, new structural elements are added to the structure. The newly placed structural element connects the node, which can freely move, with a surrounding node located in the opposite direction to the movement. After the geometry is added, the null space structural stiffness matrix is calculated again; if the addition did not reduce the structure's degree of instability the added geometry is discarded and new options are explored. The procedure is repeated until a kinematically determined structure has been achieved.

Restrictions can be set to control the way new geometry is added and which type of structural elements (trusses, beams or flat shells) are used. For example the procedure can be configured to use just one type of structural element to stabilize the whole structure; or to use different types of elements depending on the position or orientation, of the surface, in which they will be placed. This procedure is presented in depth in Smulders and Hofmeyer (2011).

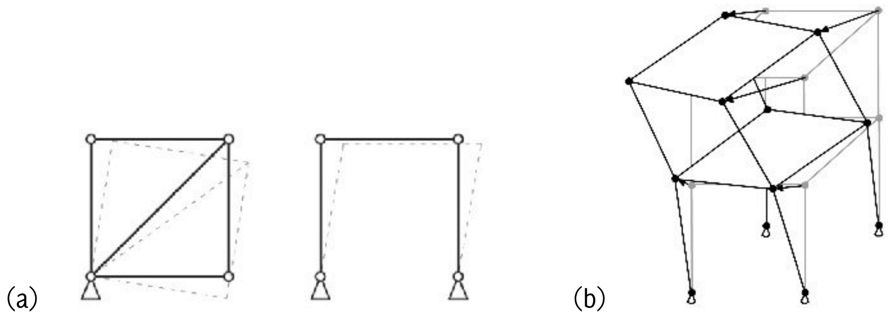

Fig. 6: Examples of Kinematic Instability (Smulders and Hofmeyer 2011)

3.2.4 FEM Structural Analysis

The structural analysis carried out in this stage is not an extensive accurate analysis; that provides relevant and specific information on the structural behavior of a given design for its possible construction. For that, specialized structural engineers must be consulted and specialized structural analysis software used.

The structural analysis performed in this process has the following objectives: (1) to give an overview of the structural behavior of the generated solution; (2) to provide useful information of the structure's spatial consequences in early design stages; (3) to set a baseline to compare structural performances between different structural solutions; (4) to set the basis for further structural optimization.

This procedure is composed of four independent methods which are briefly explained in the next sub-section.

Geometrical Redefinition

Two geometrical redefinitions occur in the Spatial Design to Structural Solution transformation process. The first one splits all zone boundary surfaces to enable correct loading of each resulting surface (Figure 7b). For instance, the light grey colored zone boundary surface is partly outside (this part should be wind loaded) and partly inside the building (this part should not be loaded). The second geometrical redefinition is carried out on the structural elements to guarantee satisfactory results in the Finite Element Analysis. To that end, the mechanical model has to be defined correctly (in terms of the connections and intersections between the geometrical elements), so when the geometrical elements are meshed (subdivided) a coincident pattern is obtained (Figure 7a).

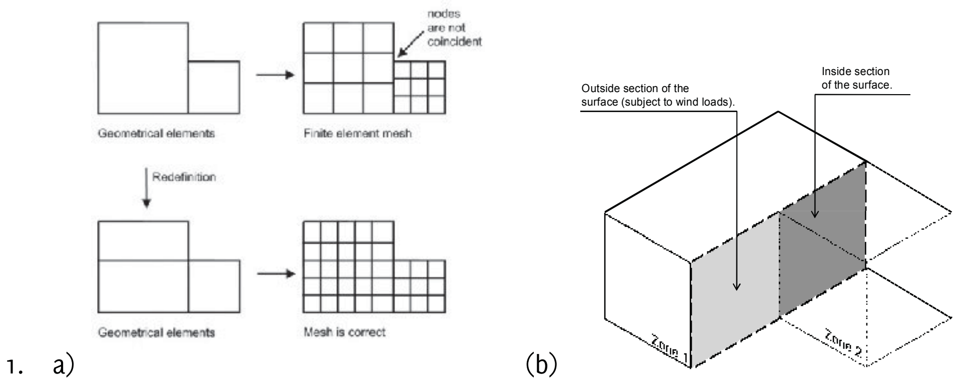

Fig. 7: Elements Geometrical Redefinition ((a) Hofmeyer et al 2010)

Note that during the second geometrical redefinition, on the structural elements, the spatial boundary lines of the split zone boundary surfaces are also taken into account, namely as "virtual structural elements". This is to aid implementing the loading method (3.2.4.3 Loading). In this way, when loads are defined, the correct proportional load of a surface is applied to the correct structural element. The geometrical redefinition method is presented in depth in Hofmeyer et al. (2010).

Meshing

The meshing method subdivides the structural elements into (smaller) finite elements. Regarding the finite element size (the mesh density), it should be noted that for FE analyses, normally the mesh density is selected such that a certain accuracy will be reached. However, within the research engine the selected mesh density may have significant further consequences. For example, due to the proposed set-up of the optimization algorithm (in the Structural Solution to Optimized Structure phase), the removal of low-stress elements will result in a coarsely or finely granulated remaining spatial design.

Two types of geometrical elements have to be meshed: linear (trusses and beams or columns) and planar (flat shells). For both the linear and planar elements the meshing algorithm subdivides them depending on a number of divisions defined by the user.

Loading

The stable structure is loaded by horizontal and vertical loads. Every structural element is subject to a gravity load; and the whole structure is subject to a wind load from a non-orthogonal direction (e.g. North-West). In this way, the structure is loaded with wind pressure, suction and shear.

Three steps are followed to assign the wind loads to the corresponding structural elements. First, the orientation of the surfaces in the Structural Zones model is determined. As mentioned previously, the Structural Zones model is aligned with the Global Coordinate System; and because the model is composed by right cuboids every surface represented in the model is perpendicular to an orientation vector (North, South, East and West). Depending on the non-orthogonal orientation of the applied load, the corresponding pressure, suction, or shear loads are assigned to the corresponding surface.

The second step is to identify the structural elements that belong to the loaded surfaces. The structural elements were split taking the boundary lines of the zone boundary surfaces into account. Therefore, if a surface is subject to a load, the corresponding structural elements which belong to that surface are loaded.

The final step is to correctly distribute the loads acting on each surface among its structural elements. The used loading method is presented in depth in Hofmeyer (2011).

Finite Element Analysis

In this part of the procedure, a finite element analysis is performed to predict nodal displacements, strains and stresses in the structure.

Three different types of finite elements are used. (1) Truss, a two-node straight element with a uniform cross section, which can only resist axial forces. (2) Beam, a two-node straight element with uniform cross section. This element can resist axial and shear forces, and bending and twisting moments. This element is based on Przemieniecki (1968). (3) Flat Shell element, a four-node flat quadratic element of uniform thickness. The element's in-plane stress behavior (membrane action) is based on the presentation of such elements in Cook et al. (1989); and its out-of-plane behavior (bending action) is implemented using the DKQ element developed by Batoz and Tahar (1982).

4. Study Case

In this section, a simple study case is presented which exemplifies the process followed by the RE to generate a structural solution (Figure 8). This section also explains how the user can interact with the tool and how the end result of the process can be altered; by setting certain controls and defining guidelines for the transformation procedures.

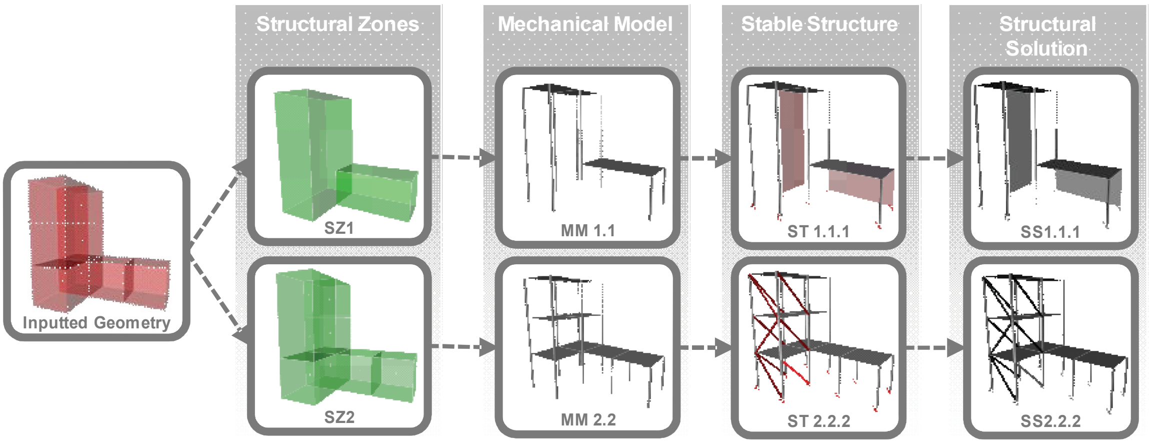

Fig. 8: Graphical representation of the Spatial Design to Structural Solution transformation process. Diverse structural solutions can be generated from a single spatial design.

A simple spatial design is used as input, to easily identify the transformations and structural solutions proposed by the tool (Figure 8 [Inputted Geometry]). It shows the capabilities of the Spatial Design to Structural Solution transformation process and its potential of fulfilling the RE aims.

The Zoning procedure was set to generate two different arrangements of structural zones. First, the procedure generated zones with the maximum possible volume; then the procedure generated the smallest possible zones. Setting the procedure to generate the smallest possible volumes resulted in a set with several structural zones (Figure 8 [SZ2]); whereas setting the procedure to generate the maximum possible volume resulted in a set with few structural zones (Figure 8 [SZ1]).

Each set of structural zones was translated into a mechanical model. The procedure to propose a mechanical model was set to use columns as vertical structural elements (Figure 8 [MM1.1 and MM2.2]); but could also be configured to use only walls or a combination of both. Depending on the used structural element the proposed structure could result in an open configuration (mainly columns) or a closed configuration (mainly walls).

The Kinematic Stabilization Procedure was set to use different types of structural elements to achieve kinematic determinacy. In the first transformation path, the procedure was set to use trusses (Figure 8 [S.T. 1.1.1]); while in the second it was set to use walls (Figure 8 [S.T. 2.2.2]). FEM structural analyses were carried out for both structural solutions.

5. Discussion and Further Development

The "Research Engine" (RE) presented in this paper aims to aid the understanding of design processes and in the improvement of design instances. In the context of the study of design processes, the RE is a suitable platform to gain academic insight on the transformations which take place in the design process, and to determine that process's influence on and relevance to the final outcome. Concerning the improvement of design instances, the RE is a useful support tool when used in early stages of the design process. Moreover the implemented transformation process (Spatial Design to Structural Solution) can be used as a generative design instrument; depending on the user's demands, the outcomes of the transformation processes will be different. Diverse structural solutions can be generated based on just a single spatial design. Information about the structural behavior of the structural solution is also generated, which allows comparisons to be made between design instances.

In future, the remaining three processes (Structural Solution to Optimized Structure, Optimized Structure to New Spatial Design, and New Spatial Design to Optimized Spatial Design) will be implemented. Although the RE is still in development, it nevertheless shows great potential to contribute to the study of design processes and in the improvement of their outcomes.

The authors wish to thank Firat Gelbal and Carola Smulders for their contribution with the implementation of the "geometrical preprocessing" and "kinematic stabilization" procedures, respectively. The work of Dennis Peeten, in the development of the graphical interface, is also acknowledged.

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A GIS-BASED INTEGRATED INFORMATION MODEL TO IMPROVE BUILDING CONSTRUCTION MANAGEMENT: DESIGN AND INITIAL EVALUATION

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ABSTRACT: *Computer and information technologies offer significant potential to improve management practices in the construction industry. However, even though all parties involved in construction rely on computers to perform their tasks, the exchange of information among the different participants during the phases of a facility is still primarily paper-based. This paper presents a GIS-based integrated visual database model that allows for effective use of computer and information technologies for communication, project documentation, and knowledge sharing among the different participants throughout the life-cycle of a facility. The model allows for (1) accessing and retrieving construction information related to a certain construction element; (2) reporting and providing feedback from the field on the work progress, quality assurance, and inspection; and (3) evaluating the performance of the construction crews and generating cost and historical data for future reference. The proposed model is built using GIS as the base platform, and uses the 2D visual representation of the construction element (i.e. the 2D CAD drawing) as the least common denominator between the different participants throughout the life-cycle of the facility. Information related to the different construction elements, such as physical and functional characteristics and project life cycle information, is linked to the 2D CAD drawing and organized in tables and forms stored in an integrated database. The paper also reports the results of an initial evaluation of the model in the settings of a construction project.*

KEYWORDS: *GIS, building construction management, information models, visual databases*

1. Introduction

Building construction depends heavily on a complex documentation process where the design intent is communicated via (a) a graphical representation of the building (which includes 2D floor-plans, elevations and cross-sections, and possibly 3D CAD models); (b) a set of specifications that dictate the quality of the components and finishes of the building; and (c) a legal document that highlights the project expectations. These three components constitute what is referred to as construction documents (CDs). Based on the provided CDs, the construction management team is able to gather information about the building (such as design information, geometric properties, etc.), add information related to constructability, resources, sequence of work, schedule, and responsibilities (this is a dynamic model, as the construction team itself is fragmented and information is generated from multiple users' inputs), and document the construction process in fulfillment of the requirements of the legal contract. As a result, throughout the stages of the project, many different types and formats of information are gathered, documented, and shared. With current practices, in part due to the variations of the level of technological sophistication of the different participants, and in part due to the legal constraints of the process, communication is carried out primarily through paper-based documents. As a result, the information and the project documentation remain highly fragmented and the information gathered or generated in one phase of the project or within one team do not transfer seamlessly to other phases of the process or to other teams.

The construction industry suffers from what has been described as the "islands of information syndrome" (Dib 2007) due to the lack of connectivity between its various participants and functions, which hampers its ability to take advantage of advances in information and computer technologies. In an attempt to link these "islands of information" among the various parties involved in the construction processes, a substantial effort has been vested in developing Industry Foundation Classes -IFC which are standard data structures that allow computer applications to exchange project information about construction projects. Approaches such as Object Oriented Computer Aided Architectural Design (OOCAD), and Life Cycle Management (LCM) also aim to improve building information modeling and communication, in the Architecture, Engineering and Construction (AEC) industry. Despite these efforts, one of the major challenges that still needs to be overcome is inadequate interoperability among computer-aided design, engineering, and software systems--this is described in the August 2004 National Institute of Standards and Technology (NIST) report entitled "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry (Gallaher et al. 2004).

The objective of the work reported in the paper was to develop and validate an innovative integrated information model interface that allows seamless sharing (among all participants) of the graphical and non-graphical information generated throughout the entire construction process. The proposed approach does not utilize the parameterized 3D model of the building as the fundamental 'smart component' of the database, rather it uses the 2D CAD drawing.

The paper is organized as follows. In section 2 we review examples of application of computer technologies to the construction industry during the past two decades, and we discuss applications of GIS to building construction management. In section 3 we describe the design and technical implementation of the proposed model; in section 4 we report an application of the model to a real construction project and we discuss initial findings. Discussion, future work and conclusive remarks are included in section 5.

2. Background

2.1 Computer Technologies for Building Construction Management: a Brief Review of the Past 2 Decades

The last twenty years have witnessed a growing interest in introducing computer technologies and tools in the construction industry. In the 1980s the focus was on gathering project data and building historical databases and models; tools such as TIME (Gray 1986), ORPLAN (Darwicke et al. 1988) and Construction Planex (Zozaya and Hendrickson 1988) were developed at this time. In the 1990s a growing interest was devoted to integrating CAD within the construction project schedule in order to exchange information and communication among the design and construction teams. Databases related to CAD applications and Object Oriented approaches were developed, such as OPIS by Froese and Paulson (1994) and COMBINE, an attempt to integrate design system to analyze the performance of a planned building (Augenbroe 1995). Around the turn of this century, 4D CAD approaches were applied to project planning. Life cycle approaches started with OSCON and OSCON-CAD by Aouad et al. (1998) and used an object oriented database linked to CAD in order to share information among various computer applications. These models focused primarily on the engineering aspect of the construction industry and did not target the construction management teams.

The last decade has seen the introduction of Building Information Modeling (BIM) technology. Although relatively new, initial experiences indicate that the creation of a parametric 3D model with associated information reduces errors of design, improves design quality, shortens construction time, and significantly reduces construction costs (Eastman et al. 2003). Due to these initial findings the popularity of BIM has grown tremendously in the past decade.

"BIM represents the process of development and use of a computer generated model to simulate the planning, design, construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and to improve the process of delivering the facility" (AGC 2005). The principal difference between 3D BIM and 2D CAD is that the latter describes a building by independent 2D views such as floor-plans, sections and elevations; editing one of these views requires that all other views must be checked and updated. In contrast, BIM represents a design as a series of parametric objects that composed together form the building model. These "smart objects" carry all the information related to the building, including its physical and functional characteristics and project life cycle information. For example, an air conditioning unit within a BIM would also contain data about its supplier, operation and maintenance procedures, flow rates and clearance requirements (CRC Construction Innovation, 2007). In reality, no single, perfectly efficient Building Information Model exists. Although the benefits of BIM to the AEC industry are widely acknowledged and increasingly well understood and the technology to implement BIM is available and rapidly maturing, BIM adoption as a construction management tool is much slower than anticipated (Fischer and Kunz, 2004). Some of the major challenges that still need to be overcome in order for BIM to become widely used include:

1. The absence of a single, widely accepted BIM system– software vendors have produced different competing (and non-compatible) BIM implementations.
2. Inadequate interoperability among computer-aided design, engineering, and software systems (this is described in the August 2004 National Institute of Standards and Technology (NIST) report entitled "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry).
3. The size and complexity of the files that BIM systems create – For complex projects, the scalability and manageability of a BIM project database represents a major challenge.
4. Sharing BIM information as drawing files – Users are used to exchanging drawings created as views of a building model rather than sharing "smart objects" from the 3D model.

The integrated information model described in the paper overcomes several of these limitations. The proposed model uses the 2D CAD drawing as the building block of the database. CAD drawings are saved in standard formats such as DWG, thus the problem of dealing with a variety of non-compatible software systems and files is eliminated (1). Although the use of an integrated database as a tool to store various types of information does not solve the issue of data interoperability completely, it facilitates user's access to heterogeneous sources of information significantly (2). 2D CAD files are not as large as 3D BIM files therefore they do not pose a problem as far as scalability and manageability (3). The information is shared through the CAD drawings and all participants in the construction process are familiar and comfortable with such documents (4).

2.2 Geographic Information System (GIS) technology in the construction industry

GIS is among the most widely embraced software technologies of the past decade. For many people, GIS is “mapping software”. More specifically, GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information, i.e., data are identified according to their locations. One of the main benefits of GIS is improved management of information resources. GIS can use information from many different sources, in many different formats and can link data sets together by common locational data, such as addresses. GIS makes it possible to link information that is difficult to associate through any other means. Thus, a GIS can use combinations of data sets to build and analyze integrated information. GIS can also convert existing digital information into a form that meets the user's analysis need. Visualization of information analysis results is an important benefit of GIS as it presents facts in a compelling way. The information can be presented concisely in the form of a map and accompanying report, allowing understanding information clearly. Since better understanding of information leads to better decisions, GIS is not just an automated decision making system but a tool to query, analyze, and map data in support of the decision making process (ESRI 2000).

GIS applications are becoming common in diverse areas such as facilities location and planning, site selection and preparation, land management, road planning, management and design, environmental monitoring and analysis, residential and commercial site surveying, public works surveys and engineering, municipal land utility surveys, infrastructure evaluation, soils modeling, and more. However, not many applications of GIS in the construction industry can be found. Willenbacher et al. (2006) studied the potential of GIS as an approach for integrating spatial analysis in building model management in order to identify changes. The objective of this work was to minimize mistakes and inconsistencies during the building life cycle. Shanmugam et al. (2005) studied the potential of GIS for meeting the increasing demands of delivering projects on a fast-track basis, where the construction begins when the design is between 35% and 65% complete. One of the key challenges was ensuring that the flow of information and deliverables between the engineering, procurement, and construction is synchronized. They conducted a study to investigate the use of GIS as a solution to increase the information flow. Results showed that GIS has the capability to effectively capture the relationships between different deliverables, record the status of deliverables, and process queries from any of the teams regarding status and impact of disruptions. Thus, it supports the decision making required for rapid development of pragmatic plans.

Aouad et al. (2005) investigated the use of GIS technology for management and maintenance of bridges and road networks. Their study showed that the use of a hybrid business and information modeling approach to develop a model to support the development ofa GIS- based bridge management system facilitates business decision making and business process change. Cheng and Chen (2002) developed an automated schedule monitoring system for precast building construction and erection of prefabricated structural components. The system, ArcSched, was developed to assist engineers in controlling and monitoring the erection process in real time. ArcSched is composed of a Geographic Information System GIS integrated with a database management system. Through systematic monitoring of the construction process and representation of the erection progress in graphics and colors, the scheduled components for erection are repetitively tracked and well controlled to implement the lifting schedule as planned. Heng et al. (2005) applied an integrated Global Position System (GPS) and GIS technology to reduce construction waste. During the study, the authors developed a prototype system to automatically capture and manage on site data for construction material and equipment (M&E) using barcodes integrated GPS and GIS technology based on the Wide Area Network (WAN) as a delivery method.

Cheng and Yang (2005) developed an automated site layout system for construction materials. The system, MaterialPlan, included a GIS- based cost estimating system integrated with material layout planning and aimed to assist managers in identifying suitable areas to locate construction materials., MaterialPlan demonstrated that GIS is a promising tool for solving construction layout problems and provides a new approach for managing spatial information in construction planning and design.

In summary, although some applications of GIS to improve the Building Construction Management process can be found, the integration of GIS and conventional construction project modeling methods has not evolved to the point where information analysis is widely conducted using spatially oriented decision-support systems.

3. The Proposed Model

The proposed GIS-based model uses the 2D CAD representation of the construction element as the basic building block of the database. The information pertinent to the various construction elements is organized in inter-related tables and every construction element is assigned a unique ID that is used as a "Key" relating the different tables. The different users access and operate different levels of the database using a user-friendly interface based on a visual Structured Query Language (SQL). The standardization of the information in the database eliminates the need for translators in order to share the information generated by the different users. The model allows for accessing the textual information from the drawing (by point and click), as well as viewing the graphical representation related to textual information in the database, thus creating a two-way connection between graphical and textual data. Figure 1 shows a screenshot of the proposed model.

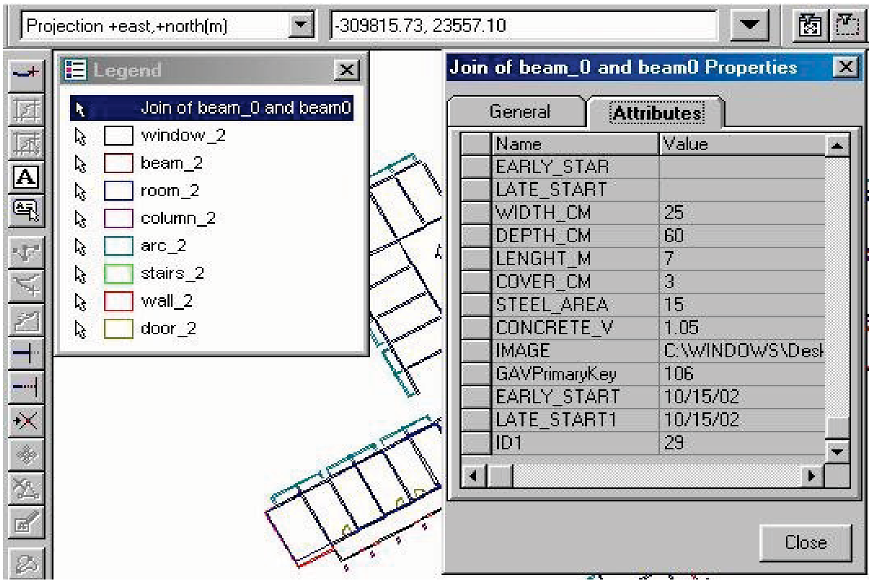

Fig. 1: A screenshot of the model illustrating the ability of the user to retrieve tabular information by pointing and clicking on the graphical representation of the construction element.

Specifically, the model links information to the graphical representation of the construction elements in order to achieve the following:

Information integration. Each construction element has a unique identification number that links its graphical representation in the CAD drawing to a series of integrated, compatible tables.

Information access. A variety of information related to any construction element can be retrieved by point and click from the CAD drawing. By pointing on the CAD representation of the construction element the user can access multiple tables on the design, safety requirements, or other tasks related to the user's job assignment.

Knowledge sharing. The user can report the work progress on-site by point and click from the drawing. The user can access the tables for work progress information and update the work in progress for that particular day.

Improved documentation. By reporting on a daily basis, and updating the work progress in the database, the user in the field can provide accurate documentation of the construction activities in the field and link the labor and manpower to the specific construction element.

Increased control. The information available from reporting the work progress and tracking labor provides the management team with reliable data that can be used to effectively manage the cost accounts and schedule progress, and monitor team performance.

Effective management of change. The tracking and the documentation of the work in progress allows the management team to measure the effect of change on the construction activities, schedule, labor and contract.

Replacement of paper-based communication. The users exchange construction information by updating the database. The tabular data provides the users with the flexibility to analyze, sort and organize the data, no paper based documents are required.

Work progress monitoring. The progress data allow the users to compare actual progress to the schedule, as described above.

Productivity analysis. The data provided by the users in the field, once organized and analyzed by the management team shows realistic representation of the teams' productivity.

Reference generation for future projects. The database can be used to generate reliable historical data for teams' productivity and costs of construction that can be used for future reference.

3.1 Technical Implementation

The proposed model has been developed using the Geographical Information System (GIS) as the base platform because of its capability of linking a database to a CAD drawing. The following steps were followed in order to achieve the integration of the database with the CAD drawing using GIS.

1. Obtain the CAD drawing from the architect.
2. Modify the CAD drawing such that all construction elements are organized in different, meaningful layers.
3. Create a Geo-Workspace in GIS. The Geo-Workspace is the area where the work will be performed. The Geo-Workspace was created as a Read-Write, and saved in the assigned name.
4. Define a coordinate system for the Geo-Workspace. In order to better represent construction data in GIS, a projection coordinates system is used. The coordinates of the points are based on the North and East coordinate system used in Surveying.

5. Create an access Warehouse. The access warehouse is the database that includes all the information related to the project.
6. Import the CAD layers into the GIS workspace and digitize them. Digitizing the information allows for defining the different elements so that all the data is vector data and has a coordinate system.
7. Connect the vector information to the data warehouse, (i.e. the database). For example, the layer "Doors" is connected to the database table titled "Doors", and so forth for all the layers corresponding to the construction elements. The information in the database table "Doors" consists of the attributes of the features in the layer "Doors".

Additional tables that are created separately in an access database format can be merged and/or linked with the tables in the database warehouse created in GIS. This allows the user to access the information in the additional databases through the queries displayed visually in GIS.

Further during the construction process, when changes occur, features can be added or modified using the editing functions within GIS using procedures similar to the ones described above. For example, additional doors can be added in the layer "Doors" and the information related to these doors is automatically added in the database table named "Doors", allowing the user to access the information in the table from the drawing, or the visual information from the tables.

The construction elements of the building are organized in a DATA FRAME that can be called, for instance, "Project X". The executive manager in construction company "Y" in charge of multiple projects has access to multiple "Data Frames". To access information related to a specific project (i.e. "Project X"), he/she will have to access the data frame titled "Project X" to be able to see information pertinent to this project. The DATA FRAME titled "Project X" consists of layers organized in groups, which are representations of the different phases of the project or the different buildings. Each group includes a list of layers corresponding to different building construction elements; each layer acts as a reference to the data contained in data sources: vector datasets-- feature layers such as CAD files, coverages, shapefiles, geodatabase, and databases; and raster datasets-- raster layers such as grids and images.

GIS as the base platform for the model allows working graphically using the CAD construction element as the unit of analysis. It also enables the user to quickly develop custom tools, interfaces, and complete applications thus making the model easy to work with in any organization.

4. Example of Application and Initial Findings

To better illustrate the functionality of the proposed information model and validate its effectiveness, one of the authors used the model in a real construction project and applied it to a particular set of construction elements: the "Walls".

The information provided in the contract documents related to the walls included the following:

- The CAD drawings showing the walls as well as other construction elements on the same drawing sheet. Figure 2 shows a portion from the contract document drawing sheet. The sheet includes the representation of a typical layout of the various construction elements as well as annotations that indicate to the user various details related to the construction elements. On this drawing the types of walls are represented in small diamond shapes with numbers; the numbers refer to the wall types and define the characteristics and the guidelines that need to be followed to provide the required items.

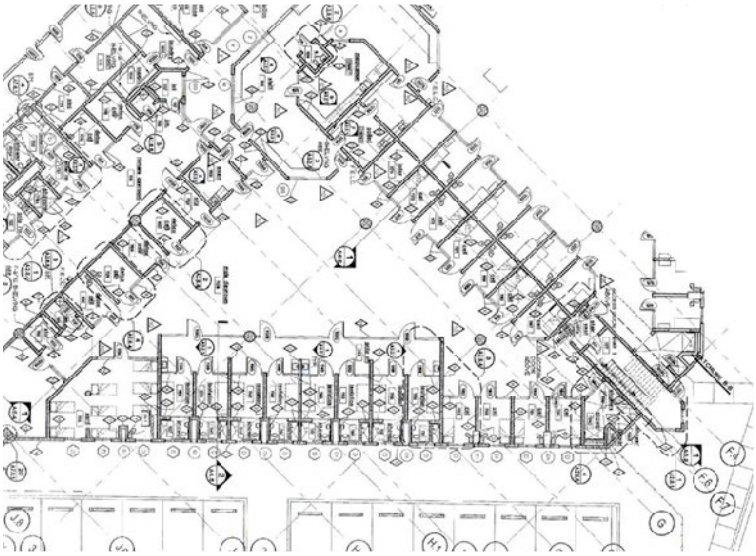

Fig. 2: CAD drawing with walls and other construction elements

- The guidelines and the specifications that the Construction Management team will have to provide such as: Preconstruction Testing Service; Concrete Masonry Unit Test for each concrete masonry unit indicated, per ASTM C 140; Prism Test for or each type of wall construction indicated, per ASTM C 13 14; Mortar Test for mortar properties per ASTM C 270, for each 5000 sq. ft. of wall area; Grout Test for compressive strength per ASTM C 1019, for each 5000 sq. ft. of wall area.

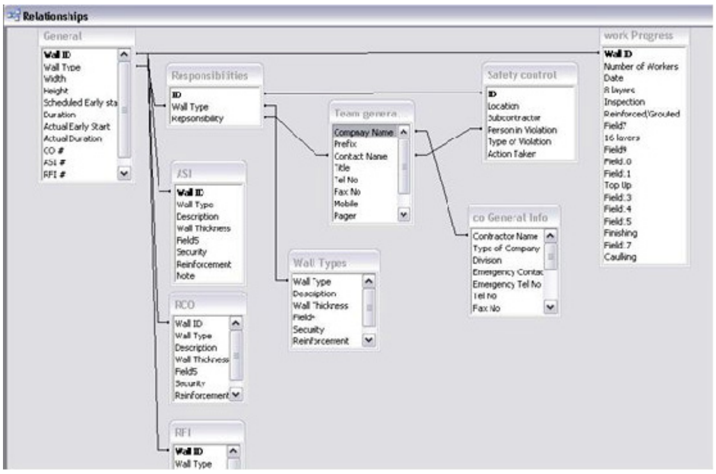

Fig.3: Tables in the relational database

- The Architect Supplemental Information (ASI) or Change Order (CO), which are changes that affect the construction processes.

In order to use the proposed model, the walls were digitized into GIS. The layer "Walls" was then connected to a table in the database warehouse that was filled with the attributes related to the different walls in this layer. The database in GIS was then connected to other database tables outside GIS. Instead of having one large and complex database table, the database consisted of independent linked tables, each one serving a specific purpose. The tables are shown in figure 3 and included:

A “General Company Information” table dedicated to the information about the Subcontractor; a “General Team Info” table used by the field superintendent to access the name and responsibilities of the different individuals in charge of the coordination tasks; a “Work Progress” table that allowed the Field Manager to track the work progress (this table contained fields such as: Wall ID, Number of Workers, Date, 8-courses, Inspection, Reinforced/Grouted, Date, 16-courses, Inspection, Reinforced/Grouted, Date, Top Up, Inspection, Reinforced/Grouted, Date, Finishing, Date, and Caulking); and a “Responsibilities” table that allocated the different responsibilities based on the wall types, Wall ID, Wall Type, and Responsibility. The “Responsibility” and “Work Progress” tables were linked by the key field Wall ID.

Using these four interconnected tables, the field manager could record the work progress by updating the work progress on site, and the project manager in the office had access to the up-to-date jobsite information and was able to generate the costs and the reports that were needed for billing, as well as compare the actual versus planned work progress.

The information presented in Figure 3 is tabulated as shown in Table 1. Initial information such as design requirements, type of walls and who is supposed to perform what task and when was determined from Table 1. The field manager could access the “General Information Access” table which included information organized in fields such as Wall ID, Wall Type, Width, Height, Scheduled Early start, Duration, Actual Early Start, Actual Duration, RCO #, ASI #, and RFI #. This table provided the information needed for the construction of the wall and could be accessed from the drawing. The field Wall Type in this table was linked to the field Wall Type in the table “Wall Types” providing detailed information about the specific wall based on its annotation. The “General Information Access” table was also linked to the table of work progress by the field “Wall ID”. Hence all the work progress was shown in this table, as both were linked together.

For tracking of changes, a table dedicated to Change Orders titled “RCO” (Request for Change Order) was created. Once the CO was accepted by the construction management team, the change was updated in the table “General Information Access” under the field RCO #, as both tables were linked through the field “Wall ID”. The same applied to the RFI # (Request for Information), i.e., information generated to clarify the scope of work, and the ASI # (for any additional information and changes requested by the Architect or Owner to be processed immediately).

Table 1: Wall types in tabular format

Wall	Type	Wall Thickness	Security	Reinforcement	Note
A	CMU	6 inch	Minimum/ Non Secure		
A1	CMU	6 inch	Medium Security		
A2	CMU	6 inch	Maximum Security		
A3	CMU	6 inch	T.O. CMU = 3'-4" AFF	# 5 @ 16" O.C. Vert	Provide Bullnose cap units at top of partial height walls per detail WT-002
A4	CMU	6 inch	T.O. CMU = 4'-0" AFF	# 5 @ 16" O.C. Vert	Provide Bullnose cap units at top of partial height walls per detail WT-002

A5	CMU	6 inch	T.O. CMU = 10'-0" AFF	# 5 @ 16" O.C. Vert	Provide Bullnose cap units at top of partial height walls per detail WT-002
A6	CMU	6 inch	Minimum/Non Secure, T.O. CMU = 8" Above F. Ceiling		
B	CMU	8 inch	Minimum/Non Secure		
B1	CMU	8 inch	Medium Security		

Figure 4 shows an example of user query for activities by "Early Start" criterion. The user could query the data according to location, content, proximity, and intersection. For example, data could be added to maps to find the geographic factors that drive trends and distributions or locations at which particular characteristics coincide. By means of Structured Query Language (SQL), the user could aggregate data geographically by categorizing it based on areas such as the different phases of the project, or based on common characteristics such all "Features = Windows" and "Attributes = "Aluminum". The user could narrow the search by adding to the selection AND "Attributes = Early Start = Today's date". Furthermore, the output from one analysis could be used as the input to the next analysis which enabled the user to create advanced geoprocessing applications.

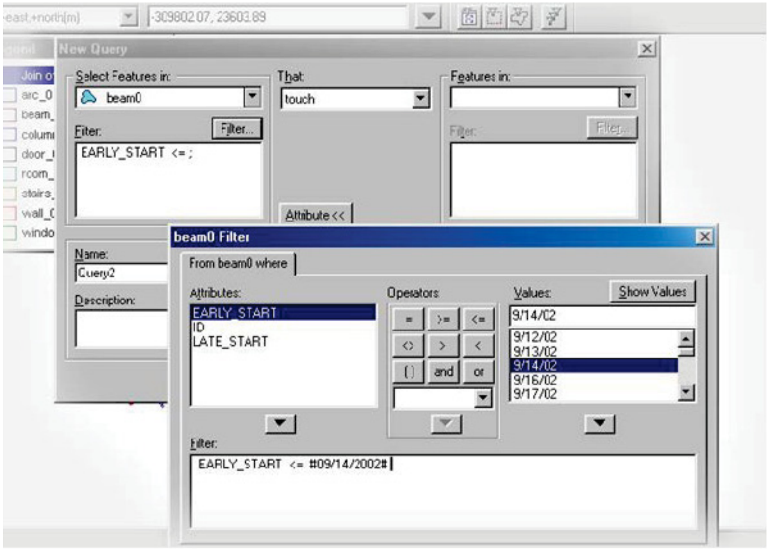

Fig. 4: An example of user query

Applying the proposed information model to a real construction project revealed the following benefits and limitations.

<u>Benefits.</u>

Using the model allowed the construction team to:

- Reduce/eliminate loss of information (all information was shared in a network-accessible database)
- Detect miscommunication at early stages, thus reducing the need for later changes
- Reduce cost overrun caused by miscommunication and changes
- Reduce time loss (less effort spent on communicating and tracking changes)

- Reduce chances of litigations (less changes, less time delays, less cost overrun)

In addition to alleviating/solving these common problems, the model offered the following additional advantages to the construction company in the construction phase:

- Flexibility to manage human resource duties
- Ability to evaluate the team members' performances
- Ability to create reliable historical data for future reference projects
- Ability to compare company performance to national averages
- Ability to compare and rate team performances vs. other teams within the same company
- Ability to collaborate and share knowledge and lessons learned among different teams within the same company

Limitations.

Using the system onsite revealed three types of limitations: legal, user-related, and cost/computer-related.

- The proposed model relies on databases and electronic filing of information therefore does not satisfy the legal requirements for documentation, as the legal system relies on paper-based documentation as the standard documentation method.
- The construction team might be reluctant to use such system since all information is shared (for instance, mistakes are documented and accessible by supervisors).
- The use of the proposed system requires computer hardware and computer literacy. Additional computer hardware means additional expenses for the construction company; computer literacy is something the current onsite construction workforce lacks. Furthermore, the system requires computers to be carried around on the construction site, which is typically not a computer friendly environment.

5. Discussion and Future Work

In this paper we have described the design, development and initial validation of a GIS-based integrated information model to improve the Building Construction Management process. The proposed model uses the digitized 2D CAD drawing as the least common denominator between the different participants throughout the life-cycle of the facility. Information related to the different construction elements, such as physical and functional characteristics and project life cycle information, is linked to the CAD drawing and organized in tables and forms stored in an integrated database. The proposed model aims to overcome many of the challenges faced by the construction team, such as understanding the scope of work, managing the construction work effectively, keeping track of the changes and the work progress accurately, and assuring compliance with the contract documents and the building codes.

Currently, the construction team relies extensively on communication through means such as faxes, photocopies, correspondence letters, phone calls, and emails. The construction information is available to the construction team in different formats such as architectural drawings, detailed drawings, general specifications, and building code. In the current situation, at any time the Project Engineer (PE) needs to look for a specific piece of information, he has to search through bits and pieces of data scattered in different formats. With the proposed model:

- GIS provides the “one place to go” for a PE to retrieve the information needed to understand the scope of work. This process gives the PE fast access to up to date, reliable information
- The database format of the information allows flexibility to maneuver the information in terms of quantity take off, costs, and dates to order materials
- By updating the GIS model once, all the different team members can have access to the latest up to date information. Furthermore, the GIS model updated by one party eliminates the need to have the Project Manager Post, the Superintendent Post, and the Field Post
- The GIS model allows for tracking the work progress effectively. The superintendent points to the work progress on the GIS model and adds relevant information such as, time of completion, percentage complete, inspection, errors, and responsibilities. Once in the GIS model, this information becomes part of the GIS database and is instantly accessible to the management team.

As mentioned in section 4, the application of the proposed system to a real construction project revealed some limitations which we believe can be solved in the near future. We plan to extend the system interface to mobile devices such that handheld devices can be used on site to replace cumbersome computers. We are in the process of designing and developing a more user-friendly interface to facilitate user’s interaction with the system and alleviate the construction team’s reluctance to use the tool. To satisfy the legal requirements of paper-based documentation, the system could be easily programmed to generate time-stamped daily print outs of the database contents.

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INTEGRATING VISUAL PRESENTATIONS OF CONSTRUCTION MULTI-MODELS: VISUALIZATION DESIGN SPACE EXPLORATION

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ABSTRACT: *Building information models are constantly extended to contain data from different domains. To allow for gaining insights for the human user, the visual representation of this data is essential. However, there is no generic and systematic approach in the field of construction information visualization which at the same time integrates existing domain specific visualization knowledge. In this paper, we define a concept for multi model visualizations, a set of relevant multi model configurations and three disjoint visualization integration methods. The spanned visualization design space is illustrated with prototypical implementations and simple data sets. Each sample of the design space is reviewed and rated in terms of its performance defined by the efficient usage of user resources.*

KEYWORDS: *BIM, multi model, visualization*

1. Problem

A building product model aggregates information about the planned building. Core of this model is the description of the future building in terms of its physical properties, mainly geometry and material. Several other models contain additional non-spatial information about the construction process, e.g. costs and schedules. These and the core building model are mutually interlinked. While for each of these models traditional visual representations exist, their combination allows for and requires visualization techniques which reflect the integration of the information aggregated in the extended building product model.

1.1 Related work

Traditionally the planned building is visually represented as architectural drawing. During the last decades the digital drawing has evolved into a full featured building product model, which is continuously being enhanced with more information. Geometric information is extended to the third dimension and further semantics are included, e.g. material. According to these extensions, the generated visual representations where extended to photorealistic 3D images. As schedule information is included (4D), time-based visualization techniques (e.g. Haque and Rahman 2009) could be employed. To reflect also cost information (sometimes labelled 5D), the respective visualization work is centred on the question of appropriate colour-schemes (e.g. Chang et. al. 2009). However, the information in the building product model contains much more dimensions and the choice of these seems to be arbitrary driven by the realms of experience and the dimensions of the Euclidian space surrounding us. Construction informatics lack a generic approach with regard to the visualization of n-dimensional construction data. An appropriate solution needs to be flexible enough to integrate existing domain specific visualization knowledge, such as engineering drawings, sketches or rough 3D models.

Contrary, in the field of information visualization many systematic classifications and graphical vocabularies exist which are actually lifted on a more semantically level (Voigt and Polowinski 2011). Studies on the formal description of visualizations (e.g. Wilkinson 2005) which are based on systematic exploration of the mapping process from raw data to the final visual representation have evolved into visualization languages (e.g. Jeffrey and Bostock 2010). Exploratory visualization focuses on the interactive connection of multiple visualizations and the coordination of several single views (Adrienko and Adrienko 2007). Although the special role of time and space is acknowledged, information visualization stays rather neglectful towards 3D visualizations. This is a drawback, as 3D information is an essential part of building information models. Although there is some research on the integration of domain specific knowledge (e.g. Gilson et. al. 2008), an approach to integrate domain specific knowledge for multi model visualization (MMV) is required in addition.

1.2 Method

After introducing the problem addressed within this paper as well as outlining the related work, in Section 2, we infer a definition of multi model visualizations from the multi model concept. Based on a classification of the multi model we define use case scenarios covering the space of potential multi models. In Section 3, concepts for the combination of several visualizations are identified, described and applied to the use case scenarios established in the foregoing section to thoroughly cover the space of possible MMVs. Finally, we analyse and discuss the constituted multi model visualization design space in Section 4.

2. Multi model visualization approach

First, we review definitions of multi models in the construction sector and derive a concept of multi model visualizations. Based on the relation between elementary models and existing visualizations we describe the relation between the multi model and the MMV. Second, we identify elementary model characteristics and multi model configurations relevant to visualizations. Third, we construct use case scenarios from the multi model configurations.

2.1 Constructing visualizations from connected elementary models

The concept of multi models as described by Fuchs et. al. 2011 defines elementary models as instances of a data model with a delimited domain. However, this definition does not imply that the model is elementary in a sense of atomicity. Hence, the same data might be modelled as one model or as several elementary models interlinked into one multi-model. The concept of partial models as proposed by Willenbacher 2002 approaches the problem top-down instead of bottom up, but introduces a similar concept. Instead of linking several standalone elementary models into a multi model, Willenbacher decomposes a singular product model into several sub models. These partial models are specific to a certain planning phase and discipline.

According to these definitions we assume the domain boundaries of the elementary models to be well-defined along profession and task boundaries. More precisely, they are inferred from the knowledge of established professions and the conceptual models used for specific tasks. Further, we assume that for each elementary model a non-empty set of visualizations exists which do not rely on data from additional models. The entire set allows for visualizing all information contained in the respective elementary model.

The visualization process can be described as a mapping of data to properties of a visualization model which can be transformed into a displayable image by an appropriate renderer. This paradigm is known as the visualization pipeline (Haber and McNabb 1990). For a given elementary model *E* we define a visualization method *v* as mapping from a subset of *E* to a set *P* of available parameters in a visualization model:

$$v: E_v \rightarrow P \; where \; E_v \subseteq \mathrm{E} \quad (1)$$

We assume that for each *E* there is a non-empty set of visualization techniques covering the data space of *E*:

$$V_E = \{v_1, v_2, \ldots, v_n\} \; where \; E_{v1} \cup E_{v2} \ldots \cup E_{vn} = E \quad (2)$$

V_E is considered to be an established set of methods to visually encode the information of a specific elementary model. Thus, the set of known visualization techniques of an elementary model represents the visualization knowledge of a specific profession and for specific tasks.

Due to the interlinking of several elementary models into one multi model, a concept for its visualization is required. Using the formulas (1) and (2) from above, we utilize the visualizations for each elementary model to reveal new visualization techniques for the multi model. Thus, a MMV spanning E_1 and E_2 is defined as

$$v: E_v \rightarrow \; P \; where \; E_V \subseteq E_1 \cup \; E_2, E_1 \cap E_v \neq \emptyset \; and \; E_2 \cap E_v \neq \emptyset \quad (3)$$

Some elementary models are not necessarily pairwise disjoint, consequently some MMVs might already be contained in the set of known elementary model visualizations. The visualization technique *v* of an elementary model E_1 is such *pseudo multi model visualization* if E_V is a subset of E_1 and at least one element of E_V is additionally contained in another elementary model E_2, hence, there is a non-empty common subset of E_1 and E_2. If otherwise the multi model visualization of E_1 and E_2 involves at least one element of each domain which is not in the common subset, we will call this visualization *proper multi model visualization*:

$$v: E_v \rightarrow \; P \; where \; E_V \subseteq E_1 \cup \; E_2, (E_1 - E_2) \cap E_v \neq \emptyset \; and \; (E_2 - E_1) \cap E_v \neq \emptyset \quad (4)$$

This MMV approach will unleash the potentials of the multi model concept as it allows for the visual, analytical exploration of multidimensional data and, thus, support the user to gain insights.

2.2 Elementary model characteristics relevant to visualization

Each elementary model of the building information model is characterized by properties such as the *author*, the *date of creation*, the purpose, the *domain*, the *level of detail,* or the *status*. Three of them, the *domain*, the *level of detail*, and the *status*, are crucial for visualization purpose. Therefor we will analyze pairs of elementary models which could be distinguished due to one of these characteristics. As the *domain* facet allows to distinguish between, e.g., costs or building model, and the *level of detail* defines the structure of the model, the more general *status* property subsumes all other model differences. This is a legitimate simplification because in terms of a multi model visualization it does not make any difference whether two elementary models are created by different authors, serve a different purpose or contain data from different sources, e.g. from planning or measurement.

2.3 Scenarios for the visualization of costs in combination with the building structure

In the following, we present three use case scenarios involving two elementary domain models (building model *B* and cost model *C*) which are employed throughout this paper to showcase our concepts. Both models can be visualized using existing visualization techniques, their models, and renderers.

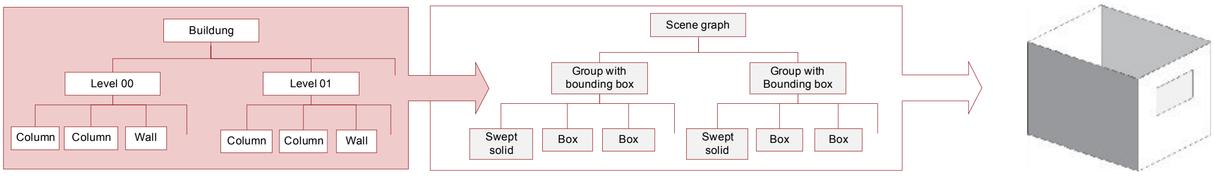


Fig. 1: Existing visualization of the geometry (building elementary model)

Fig. 1 illustrates the most common visualization method for the geometric building model as a mapping from the hierarchical spatial structure to a 3D scene graph which can be rendered as an isometric view. The spatial building model is prepared in two variations regarding the *level of detail*. The first one (*B1*) has a rougher level of detail and contains only the outer bounding geometry for each of the floor levels. The more detailed model instance (*B2*) contains the floor plan layout with rooms and walls for each floor level.

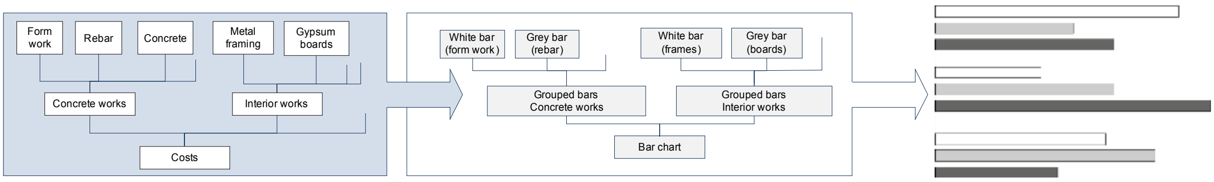


Fig. 2: Existing visualization of the cost elementary model

A bar chart as shown in Fig. 2 is a typical visualization for categorical and quantitative data. Like the building model *B* also the cost model *C* is instantiated twice. As both share the same *level of detail*, they differ with regard to their *status*. The first (*Ca*) contains planned cost values. The second one (*Cb*) refers to the actual costs after the construction work has been finished.

Our scenarios are designed along the three different characteristics of the elementary models. For a pair of model instances, we keep two facets and only change the third. The following scenarios could be distinguished.

1. Different *domains*: Elementary models *B1* and *C1* are combined.
2. Different *level of detail*: Elementary models *B1* and *B2* are combined.
3. Different *status*:: Elementary models *Ca* and *Cb* are combined.

In Listing 1 we illustrate the four model instances using pseudo-code. For the rough building geometry (*B1*) only floor heights and the outline of the level is given while for the fine-grained building geometry model (*B2*) the floor plan layout for each level is modelled as per room poly loops. The two cost model versions contain arbitrary cost values per cost category and level.

```
def model_B1 = [
  outline: [[0, 0], [20, 0], [20, 15], [0, 15]],
  levels: [0, 3, 6]
]
def model_B2 = [
  points: [[0, 0], [0, 20], [5, 20], [5, 0], [5, 10], [15, 10], [15, 0], [5, 15], [15, 15],
```

```
    [15, 20], [5, 5], [15, 5]],
  floorplan: [[[0, 1, 2, 3], [3, 4, 5, 6], [4, 7, 8, 5], [7, 2, 9, 8]],
    [[0, 1, 2, 3], [3, 10, 11, 6], [10, 4, 5, 11], [4, 7, 8, 5], [7, 2, 9, 8]],
    [[0, 1, 9, 8, 7, 10, 11, 6], [7, 8, 11, 10]]],
  levels: [0, 3, 6]
]
def model_Ca = [
  construction: [100, 200, 150],
  facade: [75, 50, 80],
  finish: [80, 120, 250]
]
def model_Cb = [
  construction: [120, 200, 220],
  facade: [75, 60, 100],
  finish: [100, 120, 120]
]
```

Listing 1: Data for the sample models

3. Visual integration methods

To represent multi model data using existing visualization techniques, we identified three disjoint integration methods to build a combined visualization technique. First, it is possible to represent each elementary model in one independent "view". To facilitate the explorational user experience, the views are interlinked. A second more integrative approach is to employ independent master and slave visualizations where the latter is (partly) integrated in the master. The most integrative approach is to blend two elementary models into one which are then mapped to a single visualization model. Therefore, mostly one dominant visualization model is enhanced by visual attributes of the second. Fig. 3 shows how different elementary models with their respective visualization models might be integrated into a combined visualization method. The integration methods are described and discussed more in detail in the following subsections. Furthermore, we briefly describe the implementation of our scenarios using the three different methods.

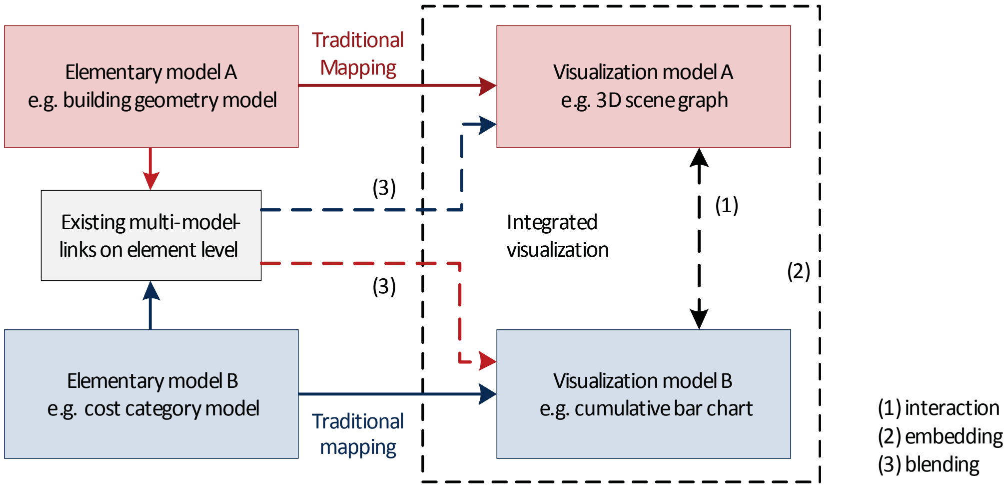


Fig. 3: Integration methods for multi model visualizations

3.1 Independent visualizations interlinked through interaction

This type of integration preserves the original visualizations and connects them through interaction. The two elementary models are mapped onto two independent visualization models and rendered into two separate views (Fig. 4). User input in one of the views produces a synchronized effect (e.g. view port properties or highlighting) in the connected one.

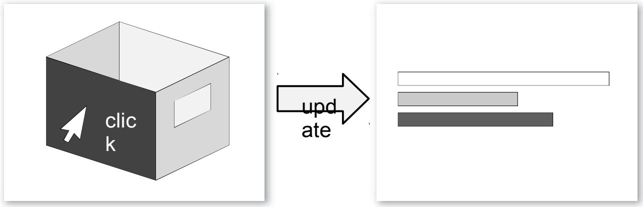


Fig. 4: Visualization integration by interaction

This type of integration allows the user to navigate autonomously, showing and highlighting distinct parts of the models by mouse clicks or other input devices. The integrated visualization might as well do without user interaction and traverse the models in two coordinated views according to a preproduced choreography. In any case it requires a visual medium with access to the users view time, hence an animated medium.

Research for this visual integration method is mostly carried out in the field of coordinated multiple views. A comprehensive overview of the state of the art is given in Roberts 2007. The implementation of flexible systems for this kind of visual integration requires proper encapsulation of the single views and their behaviour. Boukhelifa and Rodgers 2003 study how the update operations can be formally described. Apart from the area of coordinated multiple views, the Mashup approach is a prominent one which enables the integration of different data sources, e.g. elementary model, at the user interface level. Flexible Mashup frameworks like CRUISe (Pietschmann 2010) allow to encapsulate and describe generic user interface components but also special visualization components. The runtimes facilitate their context- and task-aware integration to build flexible web applications.

3.2 Primary visualization annotated with secondary visualization model parts

This type of integration denominates one of the original visualizations as host visualization and embeds parts of the other visualization as annotations into this primary visualization. The elementary models are mapped to two independent visualization models, but these models are finally rendered into one view. As an example, Fig. 5 uses the bar chart for cost data and the isometric drawing for geometric building data from our scenario. The left uses the bar chart as the host and annotates it with embedded isometric drawing visualizations, whereas the right example uses the isomtric view as the host and annotates it with embedded bar charts.

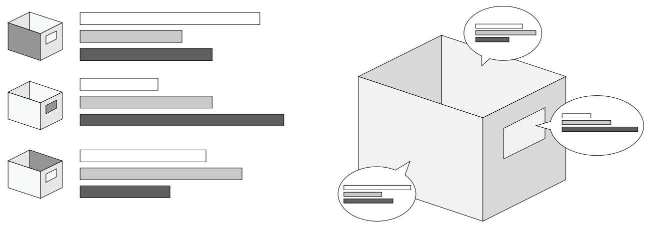


Fig. 5: Visual integration by embedding

When the primary visualization model does not contain any dedicated graphical objects, but merely serves as a positional reference frame, this concept is called “small multiples” (Roberts 2007), “worlds within worlds” (Feiner and Besher 1990) or “facets” (Wilkinson 2005). Wilkinson distinguishes the concept of facets from the one of annotations; the integration method described here spans both concepts. The former focuses on the secondary visualizations, while the latter is based on a primary visualization model with its own graphical objects and a strong relevance in the whole visual representation.

3.3 Primary visualization enhanced by visual attributes from a second model

This type of integration uses one elementary model as the primary one, and its visualization model as the exclusive only one,. Information from the secondary elementary model is employed to instantiate visual attributes of the primary visualization model. This method maps both elementary models into a single visualization model which is consequently rendered into a single view (Fig. 6).

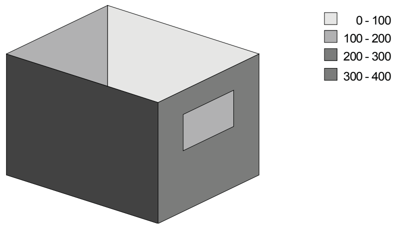


Fig. 6:
Visual integration by blending

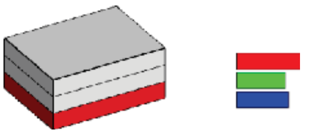
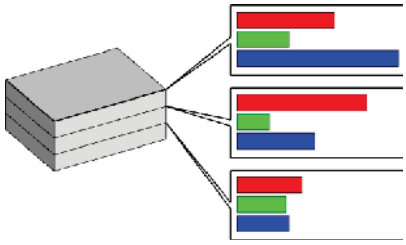
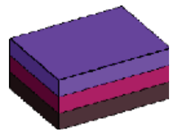
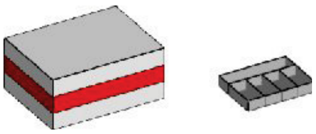
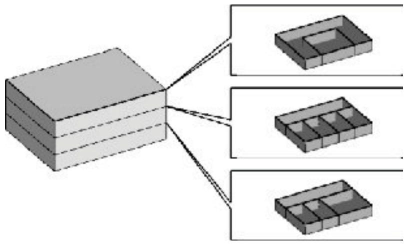
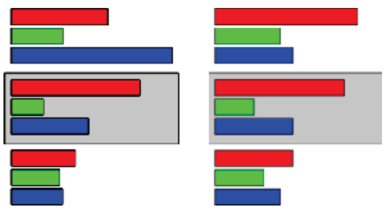
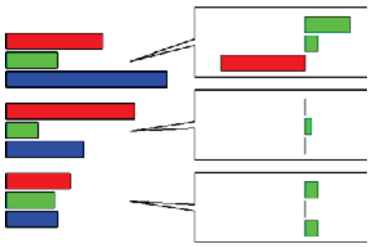
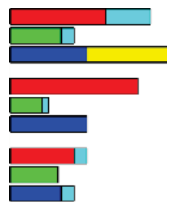
In contrast to the embedding (c.f. 3.2), this integration method relies on eligible visual attributes in the host visualization model, e.g., *colour, position* or *size*. These attributes could be assigned by values from the secondary model either because they are unused in the host visualization or because they were selectively released. While the first case requires a low density of information in the original visual representation, the latter relies on a certain amount of irrelevant information, which can be abandoned in favour of the subsequently integrated information. The most evident candidate for this kind of integration is the *colour* attribute, but there are as well visualizations with unused *size* attributes (namely most visualizations for categorical values) and attempts to partially abandon the *size* attribute without dismissing too much information (Tauscher and Scherer 2011).

3.4 Integrating visualizations for the use case scenarios

For each of the described visualization integration methods a prototypical implementation was developed using the Java-based visualization framework Processing[3]. Moreover, for each of the elementary models (*B* and *C*) a visualization technique consisting of a basic visualization model and a proper mapping was implemented. By combining both implementations in a prototypical application, the three integration methods to combine elementary visualizations are put in the context of the multi model configurations specified in the use case scenarios. In this subsection, we will discuss some details of the prototypical implementation of the three integration methods. The shows the resulting visual representation as sketches. While comparing the integration methods, it becomes clear that each method utilizes a main user resource. These user resources are listed in the last row and discussed in the next section.

[3] http://processing.org/

Table 1: Application of the visual integration methods per multi model case scenario

Integration Method	Interaction	Embedding	**Blending**
Domain scenario			
LoD scenario			
Status scenario			
Resources	interaction time	display space	reading effort

4. Results and Discussion

4.1 Efforts of the application of the integration methods to the use case scenarios

In this subsection, we will discuss some details of the prototypical implementation of the three integration methods. The interaction method was implemented straight forward with navigational slaving for the domain and LoD scenario and a basic linking and brushing interaction for the status scenario.

The integration by embedding method may produce small multiples as described in section 3.2. The primary model might be present in the visual presentation to provide context, but it might as well be left out. This is true in particular for the LoD scenario because the graphical information of the primary model is redundantly contained in the presentation with higher level of detail. Leaving out the representation of the primary model for the example scenario would produce an exploded axonometric view. Otherwise, reducing the graphical representation of the secondary model to more iconic symbols would turn the presentation into the annotation type as described in section 3.2. This is conceivable for the status scenario. To obtain consistent and comparable presentations throughout the scenarios a compromise between these special cases was implemented.

The integration by blending is implemented in a different manner for each of the scenarios. The domain scenario uses the previously unused *colour* attribute to encode cost information into the 3 dimensions of the colour space, while the LoD scenario overlays the objects to the same visual attributes for both elementary models. This is due to the uniform visualization model in this scenario. The status scenario on the other hand combines overlay and additional occupation of colour parameters to highlight the differences.

In summary, we could state that the implementation effort rises if the approach is more integrative. As the interaction approach simply employs two independent, "simply" coupled visualizations side by side, for the blending approach we need to investigated which visual means are used best and how to implement them.

4.2 Usage of Human Computer Interaction resources

The overview in In this subsection, we will discuss some details of the prototypical implementation of the three integration methods. The shows that different integration methods stress different kinds of human computer interaction (HCI) resources. We define them as resource employed at user or computer side to allow for a proper interaction between both. While integration by interaction requires often more time to interact with the visualization for exploration purpose, integration by embedding requires more display space. Integration by blending on the other hand stresses the user's cognition and ability to read the image. The mainly utilized HCI resource corresponds to the means by which each integration method represents complexity. Baldano et. al. 2009 claim the need for space/time resource balancing when designing multiple view systems. They counterbalance computational time and interaction time when updating a unique view against the space needed for several views. HCI resources in this sense include the requirements for the medium or system which produces the visualization.

We propose to extend the idea of a resource balance to include the mental effort needed to read the visual presentation. Thinking of visualization as a method of distributing graphical information in display space and viewing time, cognitive overhead is produced to correlate graphics which lie far apart (in time or space) and to distinguish graphics which are very close to each other (in time or space). Assuming there is an optimal compact distribution in time and space to minimize cognitive overhead for a certain amount of graphical information, the first kind of cognitive effort is needed when the methods utilizing time and space exceed this optimal values. The second kind is needed, when time and space resources are limited to values below the optimum. The latter kind of cognitive effort is the HCI resource utilized mainly by the blending method.

As a concurrent effect varying HCI resource utilization produces a varying strength or immediacy of emphasis on the correlations between the integrated models. From this point of view, the integration by interaction method requires the highest mental effort of the user to correlate the models because correlations in different time slots are harder to realize then in different areas of space. Correlations are most evident when graphics are near to each other in time and space as it is achieved with the integration by blending method. This is backed by psychological studies as for example on the precision of spatial judgment when 2D information is presented in either a 3D context view or in separate 2D views (Wu et. al. 2010).

4.3 Amount and structure of data as performance characteristic

The amount and structure of the data has an impact on how the different integration methods perform. Performance is defined in terms of the effective usage of HCI resources. By analysing which kind and amount of data conveys well-balanced HCI resource utilization for each integration method, we can predict for which multi model configuration the respective integration method might be appropriate.

Some of the guidelines given by Baldonado et. al. 2000 help to decide when to use multiple views. These rules, e.g., rule of diversity or the rule of complementarity can be applied to the integration by interaction method. According to these rules multiple views are appropriate for diverse attributes, models, levels of abstraction or genres and for complex comparison scenarios as well as for partitionable complex data but should be used with care, especially when the views have similar semantics. In short, if and only if data is too complex for one view and the extra navigational overhead is justifiable, it should be distributed in two views.

For the integration by embedding method, the mainly utilized user resource is space. This method is especially effective if the secondary model carries a small amount of additional information, which can be encoded using symbols. Furthermore, if the primary visualization does not contain original graphical objects, but mainly serves as a reference frame, the visualization is less space consuming, and thus more effective.

The integration by blending method is only applicable for secondary models with small amount of additional information and for primary models with low complexity or parts that are not important for the integrated visualization and may be left out in favour of a tight visual integration of the elementary models.

4.4 Per scenario conclusions

The domain scenario is likely to be complex enough for the integration by interaction method, given that the sub models involved in the two visualizations do not overlap. In contrast, the integration by embedding and blending methods will not fit the scenario under these conditions. These methods will only perform, if it is possible to pick a dedicated aspect of one of the elementary models. More precisely, if the primary model can be reduced to serve as a reference frame for small multiples, integration by embedding might be appropriate. Otherwise, if the secondary model can be reduced to replace a single property of the primary model, integration by blending is applicable.

For the LoD scenario the amount of information in the secondary model is always higher than the amount in the primary model. This causes the integration by embedding and blending methods to use space and cognition resources heavily. The information of the primary model is contained in the secondary model implicitly because the primary is an aggregation of the secondary model. To this, the integration by embedding method seems appropriate, because the more abstract information in the primary model is qualified for an abstract reference frame without dedicated graphical objects. Complexity in this case depends on how detailed the secondary model is compared to the primary model. The integration by interaction method is suitable with inversed navigational slaving, such that navigation occurs in the more detailed view and the overview view is updated accordingly. The integration by blending method can be revised to include capabilities to navigate the different levels of detail and those evolve to an enhanced integration by interaction variant with both models in one view. This is possible because of the similar semantics of both elementary models.

The complexity of the comparison scenario depends on the extent to which the data to be compared varies. The amount of information can be compressed by calculating a delta model and using this as the secondary model; the more equal the elementary models are, the better is the compression. Hence, for elementary models differing only slightly, the integration by embedding or blending methods are more appropriate than integration by interaction. As described for the LoD scenario, a combination of integration by interaction and blending with context switching in one single view can help to relate and compare elementary models with a substantial difference.

5. Summary and outlook

Based on the definition of construction multi models we have defined a concept of multi model visualizations. These visualizations facilitate the integration of existing domain specific visualization techniques by combining elementary model visualizations. We identified three fundamentally different methods for the visual integration of elementary model visualizations and applied them to scenarios derived from three basic multi model configurations. The established matrix covers the design space of multi model visualizations exhaustively. Each element of the matrix was reviewed in terms of HCI resource efficiency. As a result we made well-grounded predictions for the capability of each integration method in the context of each multi model configuration scenario.

In a next step the predictions will be evaluated based on real scale data from construction projects. In order to apply the visual integration methods to these data, the prototypical implementations have to be integrated in current frameworks for multi model data access and analysis.

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SIMULATION IN CONSTRUCTION

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ABSTRACT: *In the course of the research project mefisto 'simulation in the construction industry' was studied. Technology and models in use for simulation were examined and described. The building site planning was realized with detailed 3D models to describe all production processes in sufficient manner. The 3D models were created using mechanical engineering CAD. In this way the building is completed by construction machines, for example cranes, formwork, scaffolding and so on. The intention of the simulation process is to find the best possible variation and the maximum optimisation. This will be shown in a model-based and event-based simulation, describing the critical production processes of columns. The state of the developing work is presented and necessary improvements are described. In the construction industry the use of simulation is unfortunately not common. The possibilities and the added value of using a simulation will be pointed out to promote the use of simulation methods.*

KEYWORDS: *Optimising the production process – virtual construction site – parametric modules – adapting parametric modules - simulation – construction variants- visualisation of results*

1. Introduction

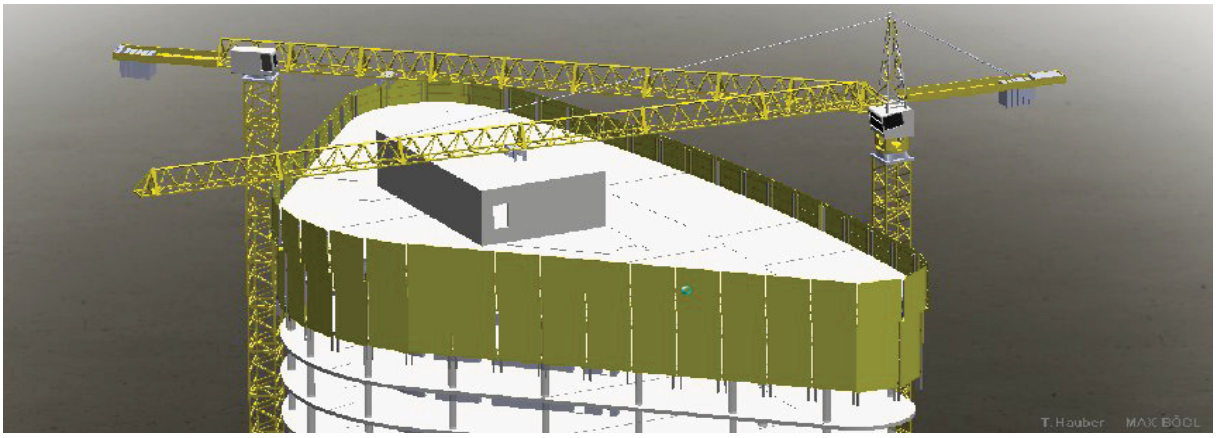


Fig. 1: Virtual construction site

Although the fundamental idea of optimising the production process is not new, the increasing possibilities in computer hardware and software technology pave the way for many new opportunities and simulation methods that can now become a reality. Attracted by these opportunities there is the will and the passion to start action and bring the process forward.

So, in the course of the research project mefisto, simulation in the construction industry was subject of study. In a virtual construction site, completed by virtual construction machines, simulation of the building process is well on its way. It is to be expected that Simulation methods will be a successful new instrument in the hands of creative engineers. The following pages will show the quintessence of our research about simulation in the construction industry and we hope to inspire all interested readers.

2. State of the Art

Simulation is applied in the mechanical engineering industry exceptionally in the automotive industry. These simulation methods have attracted much attention and recognition in the research world as well as in the world of the experts. The attempt will be undertaken to present an overview of the state-of-the-art development. In the car building industry the information from the virtual models operates the real production process. The complete design, the calculation of costs and the project controlling is based on virtual models. In the production automation takes place and numerical controlled turning, boring and milling machines are directly operated from virtual models. Similarly the work steps in the plant are subject of interaction with virtual models. Ideally the design and production chain is realised without any break. In general all relevant processes are subject of simulation. In the construction industry the use of simulation is not common.

Fig. 2: Virtual three-dimensional model

3. Statement of Problem

Sometimes some production processes run out of control. The costs may increase and the whole process could run out of schedule. Engineers in the construction industry have to face more and more sophisticated and complex problems. Sometimes the whole construction site went astray. For those reasons there is a high interest in having effective instruments in project controlling. So the attempt was undertaken to find out if recent developments in software and hardware technology can provide a solution.

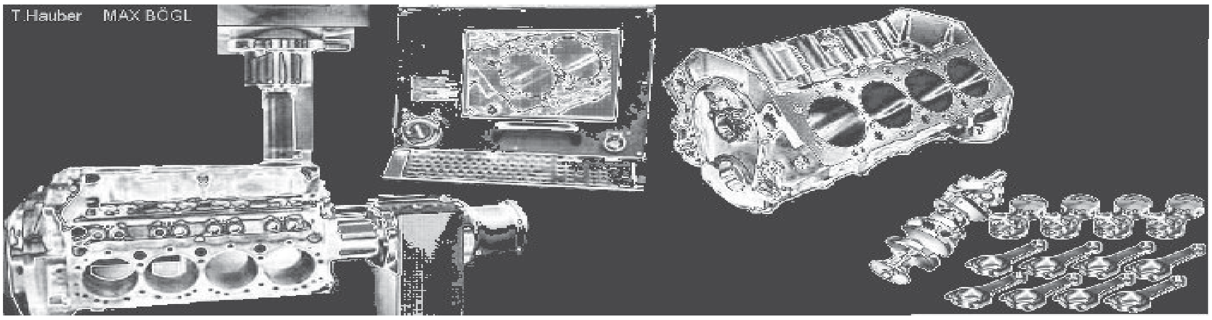


Fig. 3: Production with numerical controlled machines

3. Statement of Problem

Sometimes some production processes run out of control. The costs may increase and the whole process could run out of schedule. Engineers in the construction industry have to face more and more sophisticated and complex problems. Sometimes the whole construction site went astray. For those reasons there is a high interest in having effective instruments in project controlling. So the attempt was undertaken to find out if recent developments in software and hardware technology can provide a solution.

4. Method of Resolution

Our vision of an effective instrument in project controlling means a comprehensive representation of the entire construction site with all of its components. In addition we want this instrument to support strategic decisions or even confirm strategic decisions. To realise the vision all conditions under which the project takes place are to be described as exact as required to establish a virtual construction site where the production process can be analysed, simulated and optimised as far as possible. In other words: The digital representation of the construction site offers the frame to research the virtual construction process as a synonym for the real and physical process on the building site. This is the major crux to be solved.

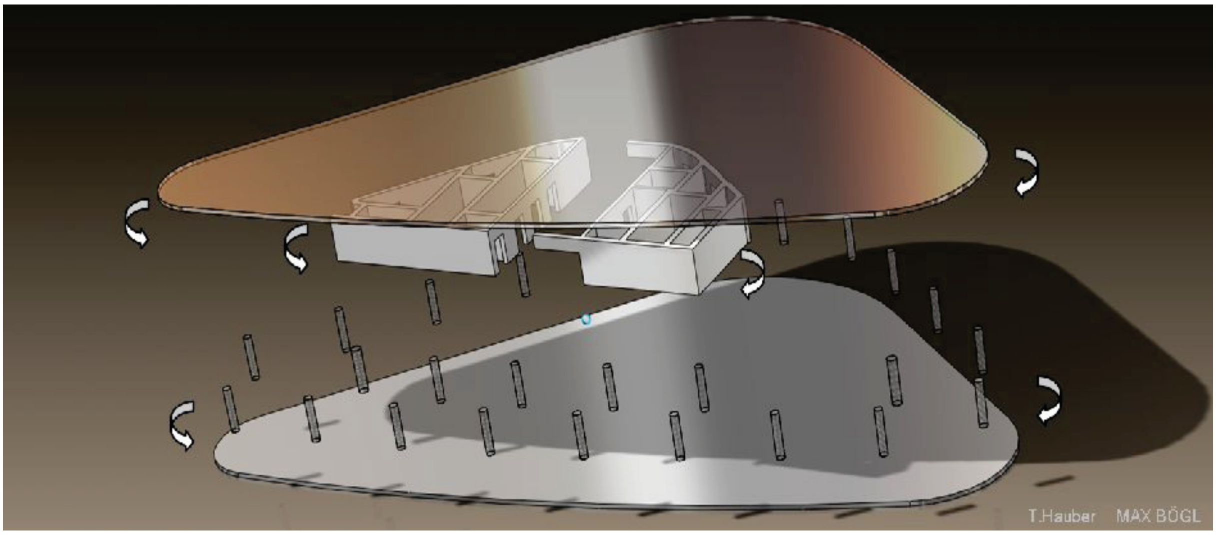


Fig. 4: Components of the construction site

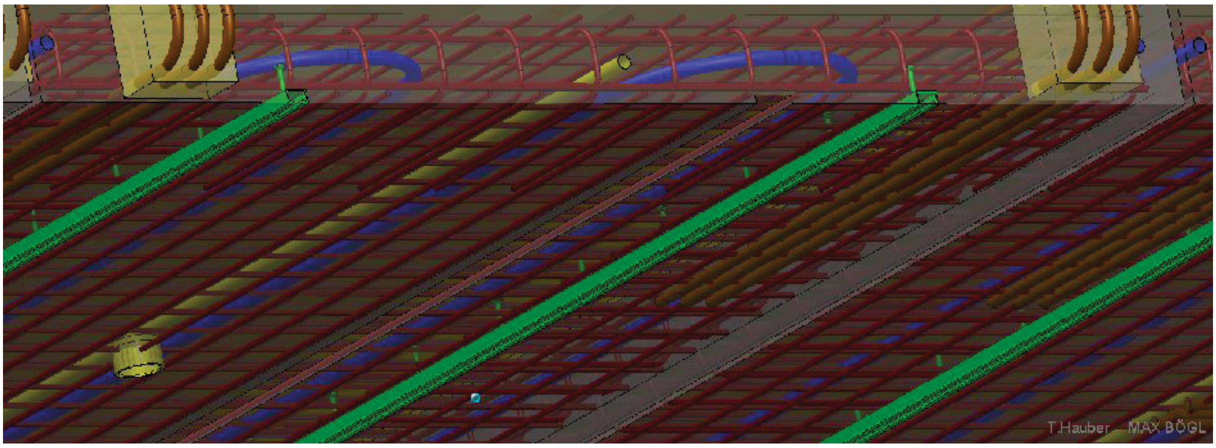


Fig. 5: Representation of all components

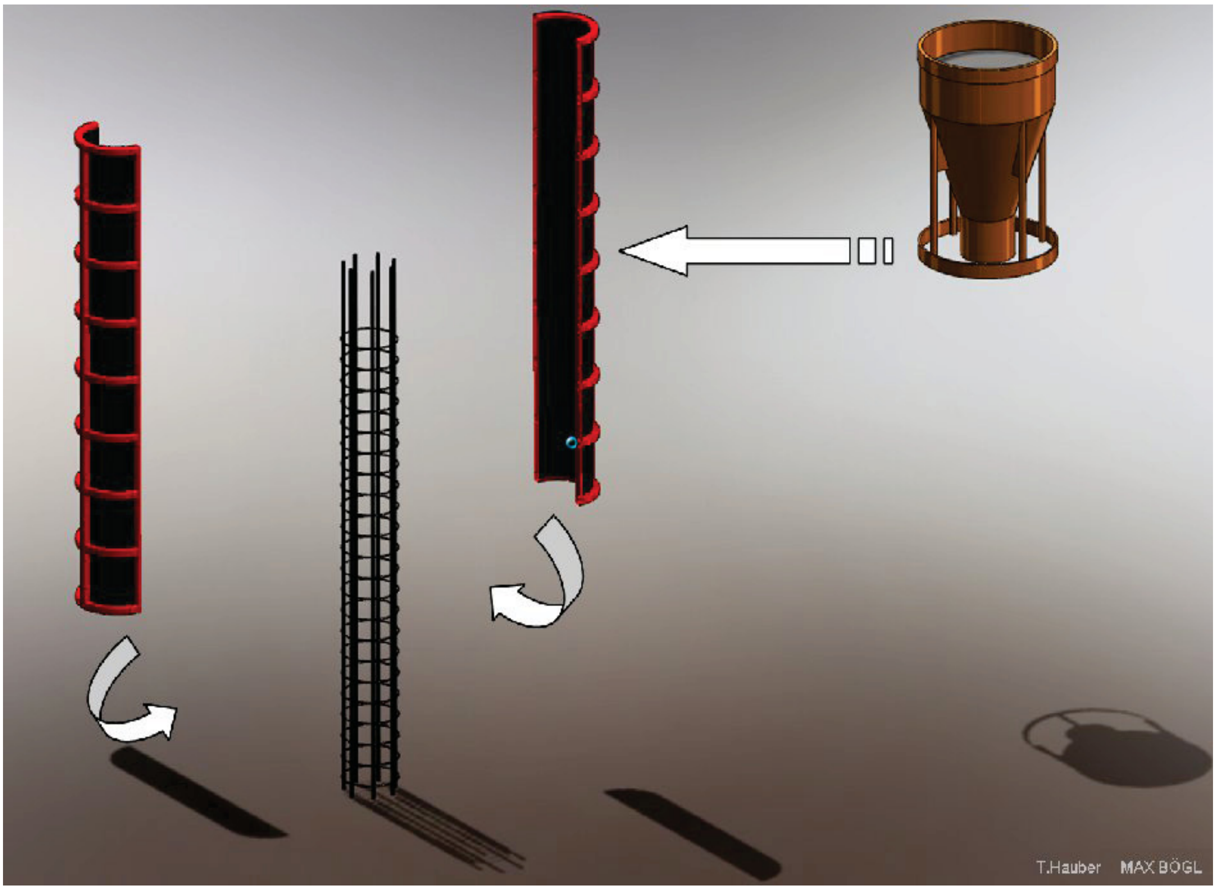


Fig. 6: Representation of the production process

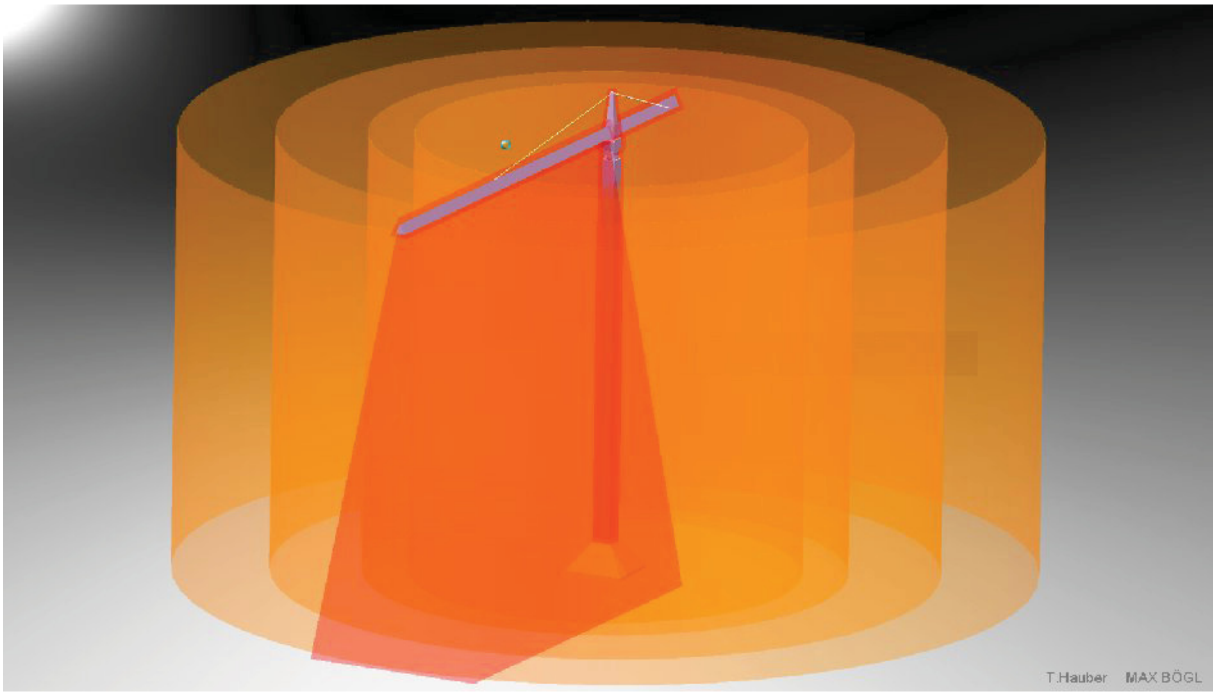


Fig. 7: Crane added to establish a virtual construction site

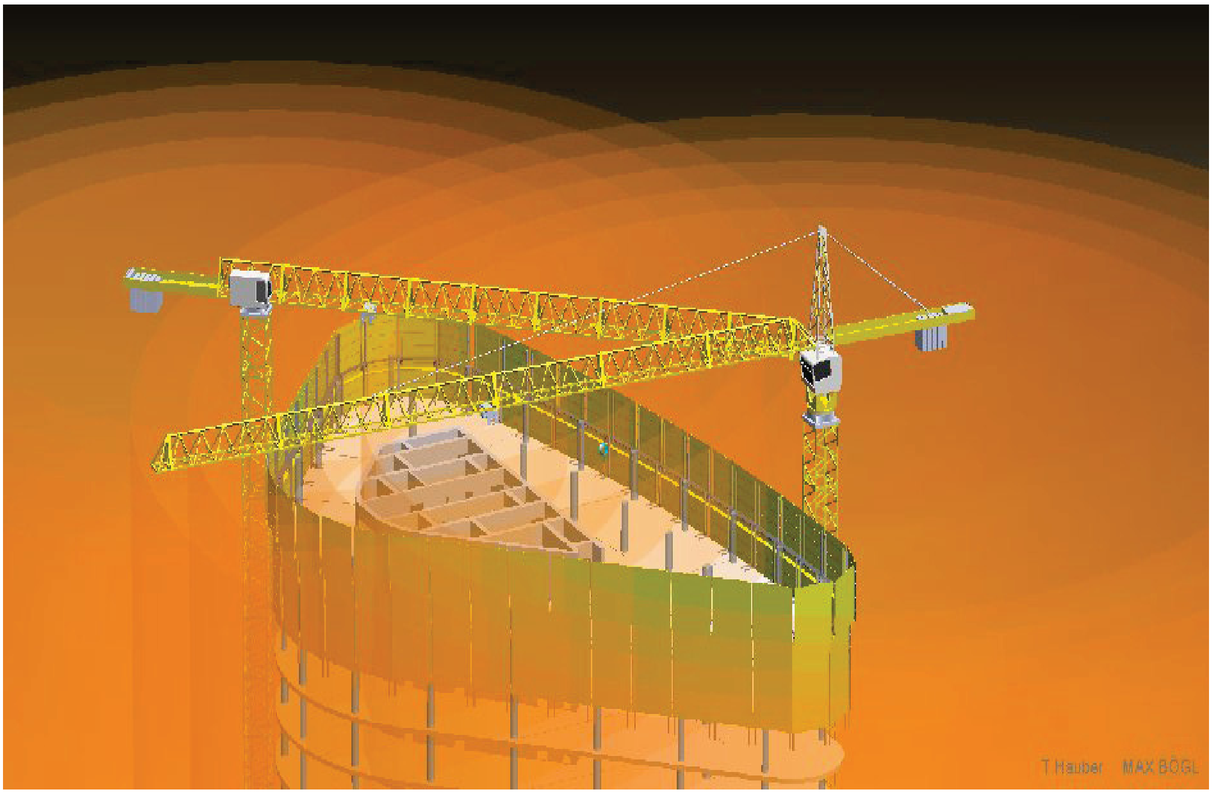


Fig. 8: Virtual construction site of the high-rise building

An example illustrates the use of simulation methods in project development and project controlling: Starting point is the three-dimensional model representing the virtual construction site of a high-rise building. The design of the building was finished and released together with a schedule.

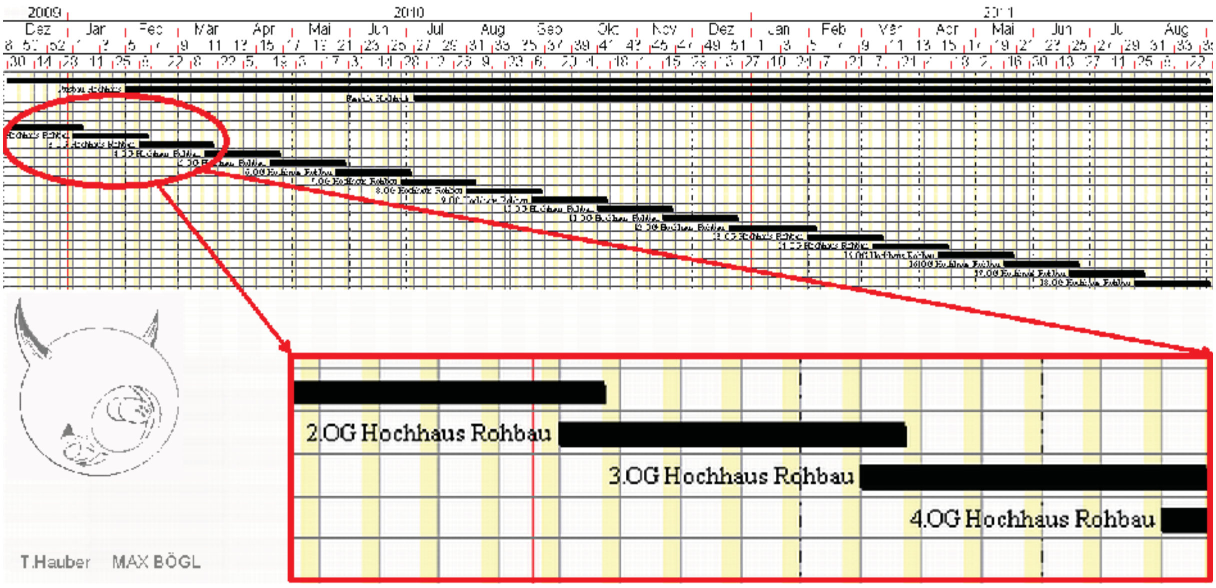


Fig. 9: Schedule of the high-rise building

Although most buildings are unique many production processes on the construction site are similar. To be able to consider the differences, the virtual construction site consists of parametric objects, so called process modules. Also formwork, scaffoldings, cranes and other construction machines are parameterised and can be adjusted to the technical demands of the construction site layout. Finally the virtual construction site represents the reality in a way that allows to detect and to solve possible geometrical conflicts. In our example the simulation describes the interaction between the building elements, the involved workers and their work as well as the used machines. After calculating some scenarios the simulation pointed out that the construction process is running behind schedule. Rationalisation of the work routines also could not solve the problem. Visionary development and testing of variants by use of the virtual construction site finally disclosed a solution. By using a support block the construction process of the columns can be greatly improved. The virtual construction site is also used for the visualisation of the simulation results and, in addition, for an interpretation of the simulation results by experts.

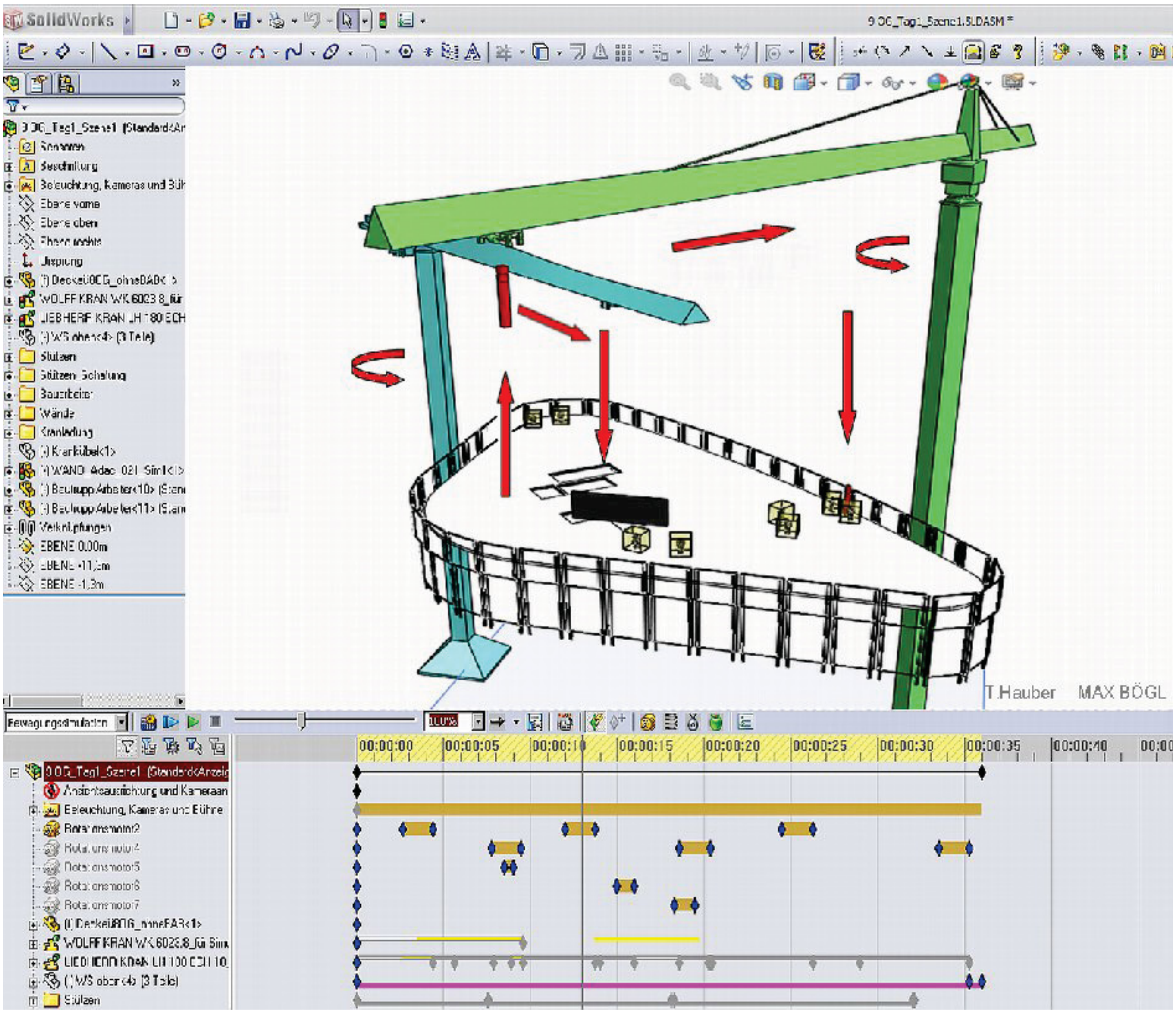
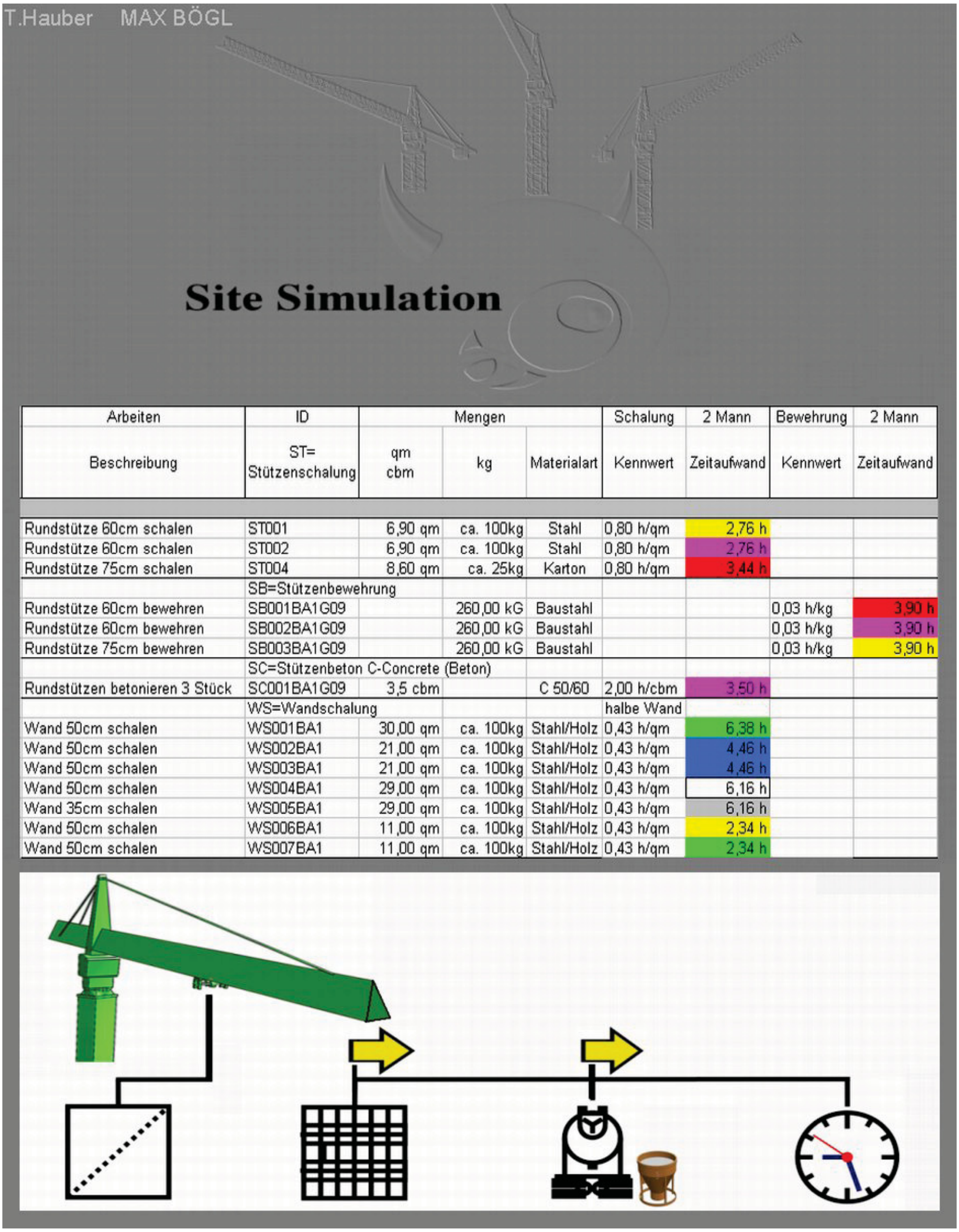


Fig. 10: Production processes on the virtual construction site

The three-dimensional model of the construction site with all cranes and other construction machinery was realised in the mechanical engineering CAD Solid Works.

The simulation process was supported by the extension SiteSimulation.



Arbeiten	ID	Mengen			Schalung	2 Mann	Bewehrung	2 Mann
Beschreibung	ST= Stützenschalung	qm cbm	kg	Materialart	Kennwert	Zeitaufwand	Kennwert	Zeitaufwand
Rundstütze 60cm schalen	ST001	6,90 qm	ca. 100kg	Stahl	0,80 h/qm	2,76 h		
Rundstütze 60cm schalen	ST002	6,90 qm	ca. 100kg	Stahl	0,80 h/qm	2,76 h		
Rundstütze 75cm schalen	ST004	8,60 qm	ca. 25kg	Karton	0,80 h/qm	3,44 h		
	SB=Stützenbewehrung							
Rundstütze 60cm bewehren	SB001BA1G09		260,00 kG	Baustahl			0,03 h/kg	3,90 h
Rundstütze 60cm bewehren	SB002BA1G09		260,00 kG	Baustahl			0,03 h/kg	3,90 h
Rundstütze 75cm bewehren	SB003BA1G09		260,00 kG	Baustahl			0,03 h/kg	3,90 h
	SC=Stützenbeton C-Concrete (Beton)							
Rundstützen betonieren 3 Stück	SC001BA1G09	3,5 cbm		C 50/60	2,00 h/cbm	3,50 h		
	WS=Wandschalung				halbe Wand			
Wand 50cm schalen	WS001BA1	30,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	6,38 h		
Wand 50cm schalen	WS002BA1	21,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	4,46 h		
Wand 50cm schalen	WS003BA1	21,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	4,46 h		
Wand 50cm schalen	WS004BA1	29,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	6,16 h		
Wand 35cm schalen	WS005BA1	29,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	6,16 h		
Wand 50cm schalen	WS006BA1	11,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	2,34 h		
Wand 50cm schalen	WS007BA1	11,00 qm	ca. 100kg	Stahl/Holz	0,43 h/qm	2,34 h		

Fig. 11: Extension SiteSimulation

5. Summary

As part of the research project mefisto the virtual construction site describes our vision for a modern construction process. Simulation methods meet the demands within the construction industry and will have significant impacts in engineering practice. Simulation is able to support decisions and could help to find the best variant of the production processes. There is a general interest for simulation methods and if executed in a virtual construction site, they provide a unique platform for experts to find the optimal way to do what has to be done.

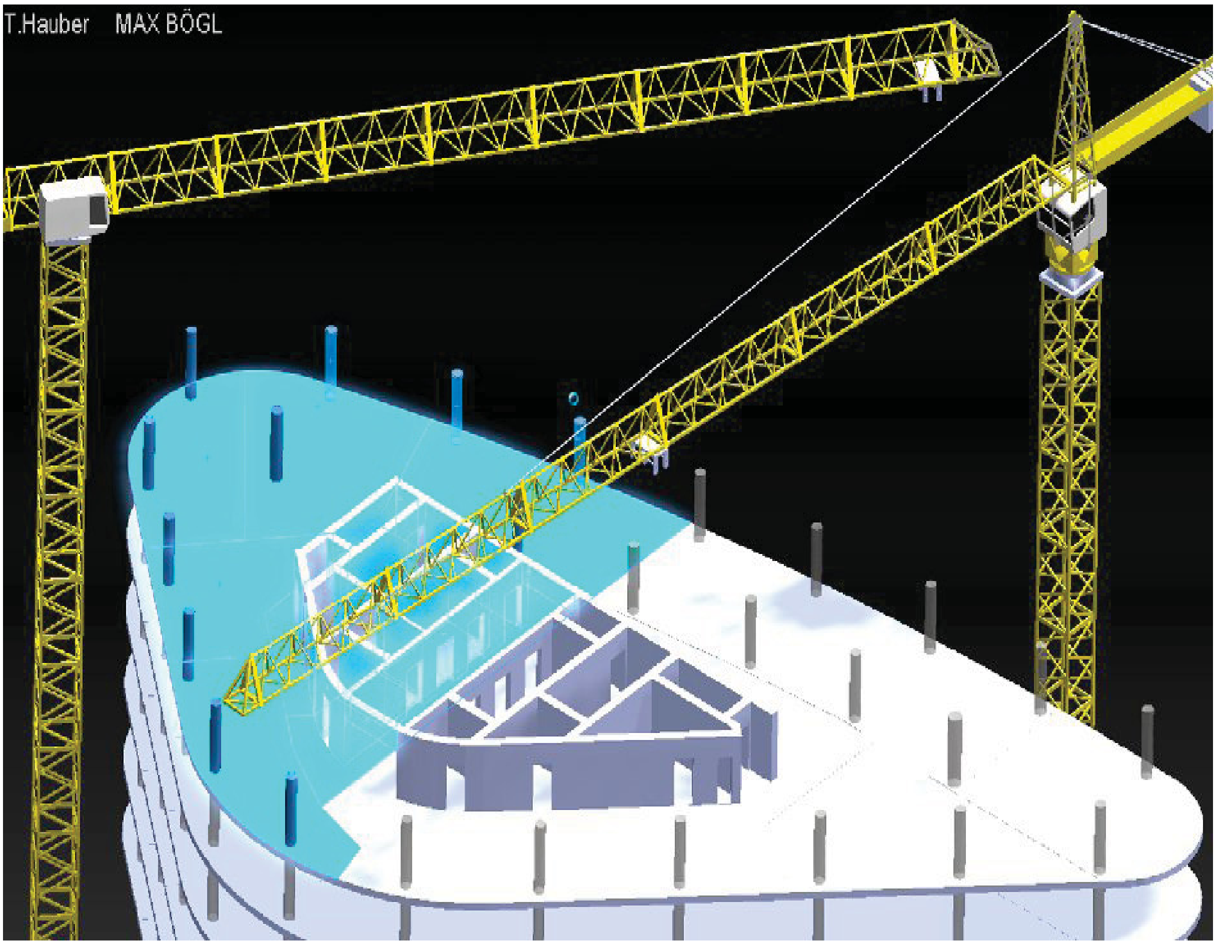


Fig. 12: Visualisation of the simulation results

6. References

References must be sorted alphabetically in the section "References". Modified Harvard style of referencing must be used. For example:

Jones A. S. (1994a). The future of electronic publishing, Journal of modern communications, Vol. 3, No. 5, 213-232.

Smith A. S. and Jones A. B. (1994). Published electronically, Proceedings of 4th international conference of office systems (Jones A. B., editor), University of New Brunswick, 213-232.

REPRESENTING PROJECT INFORMATION SPACES BASED ON SEMANTIC MULTI-MODEL ANNOTATIONS

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ABSTRACT: *The paper presents concepts and early developments for the use of semantic annotations in model-based collaboration and decision making on construction projects. In the German research project Mefisto a Management Information System for construction planning and management is realized by a semantic service platform. On the platform existing software applications are extended to allow for linking as yet disparate engineering and management models in so-called multi-models. To support the collaborative use of the multi-models the multi-model container (MMC), an exchange format for multi-models, as well as an ontology framework for their uniform annotation have been developed. The paper focuses on the use of semantic annotations to describe the content of multi-models and to represent the overall information space of all multi-models created on the platform. The first part describes the concept and content of multi-models and discusses their creation and use throughout construction planning and management. The second part of the paper introduces the ontology framework and the methods used to define annotation vocabularies.*

KEYWORDS: *multi-model, management information system, construction management, semantic annotations*

1. Introduction

Collaboration between building owners and contractors is still hindered by the heterogeneity of engineering and management models and the lack of explicitly defined collaboration processes. To share information among design, planning and ongoing construction processes interoperable connections among the software systems need to be established. Support is also needed to combine information from the different application models to analyze the coherency of project plans, to predict the performance of the building and the production processes as well as to utilize the analysis results for decision-making.

Given these shortcomings our research focuses on the development of model-based Management Information Systems (MIS) to better utilize construction project information and to support decision-making on different management levels of the project organizations. In the research project Mefisto such a MIS is implemented by a Web service platform, called the *Mefisto platform* (Scherer and Schapke 2011). Fundamental to the design of the MIS and the platform is the assumption that project collaboration in the construction phases cannot be enabled via one central project model or database. Different project participants will continue to use distinct engineering and management models optimized for their specific application domain.

On the Mefisto platform existing software applications are extended to allow for linking as yet disparate engineering and management models in so-called *multi-models*. To allow for sharing these multi-models among different project participants semantic specifications for these multi-models as well as a basic Web services infrastructure were developed. The *semantic specifications* comprise (1) the multi-model container (MMC), a data format for exchanging multi-models, (2) a selection of selected and newly developed data formats for the exchange of engineering and management information as well as (3) an ontology framework to support the uniform annotation of the multi-models in the container. The *platform infrastructure* is established by existing engineering and management applications that are complemented by a common Web service interface as well as some central platform services. The central services first of all allow for the management of users, services and multi-models on the platform. Moreover, filter and mapping services support the transformation of multi-models as well as a workflow service allows for the coordination of multi-model creation and use throughout the project organization.

The paper focuses on the use of *semantic annotations* to describe the content of multi-models and to represent the overall information space of project information on the platform. It is structured in two parts: The first part describes the concept of multi-models and their content. Moreover, it examines the multi-model operations that are needed to effectively create and utilize multi-models in planning, controlling and decision making. The second part of the paper introduces the ontology framework and the methods used to define annotation vocabularies.

2. Multi-Model-Based Project Information

The basic idea of a multi-model is to combine selected engineering and management models , in single information resources. Within the resource these so called *application models* are bound together by *link models* that explicitly specify the relations among the models interrelating associated model elements. The aim for using multi-models is to allow for *asynchronous collaborative work* on distributed, yet interdependent engineering and management models. Instead of a central all-encompassing project model numerous local multi-models are envisioned that integrate selected application models for specific planning and controlling tasks. On the Mefisto platform these multi-models are created by local AEC software applications that have been extended to interlink the internal model data with related application models. This way project participants may continue to work on local, task- and discipline-specific application models considering external project information either (1) a priori by creating a new application model as an extension to a given multi-model or (2) a posteriori by creating a new multi-model from a selection of finalized application models.

The combination of application models in multi-models provides for new ways of *model-based planning and decision-making* (Scherer and Schapke 2011). The resulting compound model represents a business object that does not only bundles selected application models, but also allows for:

- *Information integration, coherency and consistency checking*: The links in a multi-model allow for a systematic identification and documentation of the interdependencies among selected application models. Given these interdependencies the coherency and the consistency of the contained engineering and management information can be verified, visualized and further examined.
- *Build-up of supplementary analysis models*: The generic approach to interlinking application models supports the exploration of novel combinations of project information. In the Mefisto project

particularly process-centric and time-depended multi-models are built that can be used to simulate construction execution processes as well as to generate prognoses of project risks and performances.

- *Coordination and documentation of multi-model creation and use*: Multi-models can be used to capture the results of finished as well as the input to future business activities. To specify the content, scope and formalization of new project information that is to be created, a multi-model may include templates for application models as well as a workflow model that indicates the responsible actors and respective deadlines. Similarly, a multi-model can document the execution of a manual design and planning or an automated checking and analyses task combining the input and the output models in a new multi-model.

In their entirety the multi-models created by different project participants on the platform represent a *multi-dimensional information space* of interdependent application models. Sharing some of these multi-models throughout the project organization, synchronization points can be established that provide well-defined snapshots of the overall project information and a basis for subsequent planning and controlling tasks. The following four sections introduce key methods and technologies for multi-models developed in the Mefisto project.

2.1 Multi-model container

In recent years an increasing number of 4D and 5D software applications have been developed that allow for complementing Building Information Models with related engineering information. While applications such as Navisworks© (Autodesk Inc.), iTWO© (RIB Information Technologies AG), Synchro© (Synchro Ltd.) and Vico Office Suite© (Vico Software, Inc) support the import and analyzes of engineering models in numerous data formats, there are no established forms to exchange the generated multi-models.

For sharing multi-models in Mefisto a new exchange format named the *multi-model container (MMC)* was developed (Fuchs et al. 2011). In contrast to a straight application or extension of Building Information Models, the container only defines a superstructure to capture different kinds of application models and corresponding link models. On the Mefisto platform the multi-model container is realized by a collection of data files that are exchanged within a compressed archive file as illustrated in figure 1, left. The root element of the collection is a XML-based description of the multi-model holding elementary models, link models and respective meta-information by URI-references or in embedded CDATA.

An *elementary model (EM)* is a serialized instance of an application model. Within the container it is treated as independent information resources with its own application domain, specific model schema and data formalization. This allows for the utilization of existing: (1) data format that have been established in different industry areas and countries as well as (2) software applications that have been developed for specialized application areas and do not integrate current Building Information Models. A *Link Model (LM)* is a serialized collection of link objects explicitly specifying the interdependencies among a set of elementary models. The link objects (depicted by the white knots in figure 1, left) within the link model represent objectified n-ary links and may hold references to a number of m elements (depicted by the grey knots in figure 1, left) from the n elementary models. The *meta-information* allows for the annotation of the elementary models and the link models describing their content in accordance to the ontology-based model framework discussed in section 3.

2.2 Application model domains, formats, views and templates

While the multi-model container provides for a flexible utilization of data formats, additional guidelines need to be established for the coherent structuring of the contained application models. Hence, a set of data formats was appointed for the exchange of application models on the Mefisto platform. Moreover, model views were specified that represent typical subsets of an application model as well as respective templates for multi-models were defined. Figure 1 illustrates the application models, link models and corresponding meta-information of an instantiated multi-model (figure 1, left) as well as of a multi-model template (figure 1, right).

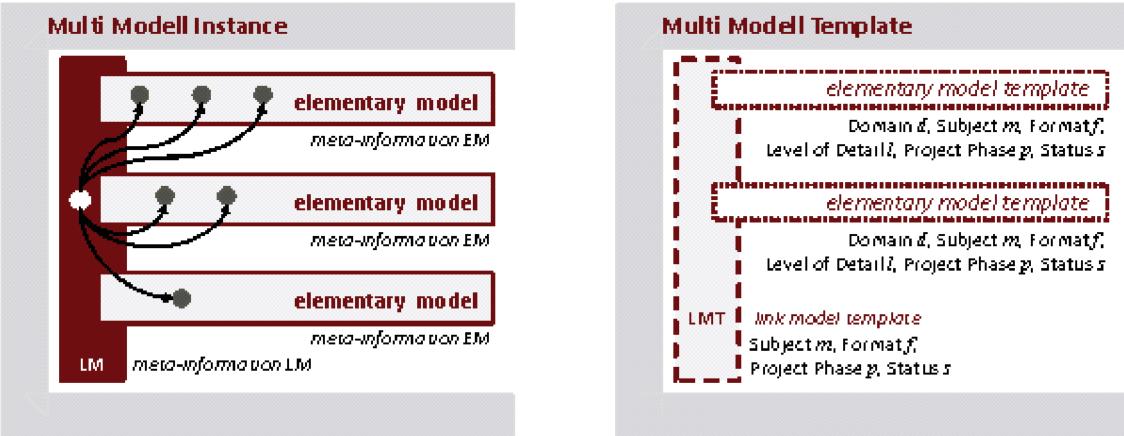

Fig. 1: Multi-model containers with instantiated application and link models or only meta-information

The data formats for the application models were selected in a three-step process. First, the engineering and management models used in construction planning and management today to describe construction project were classified in nine *application model domains*. Second, standard and proprietary *data formats* were identified to cover these descriptive domains as well as some new schemas were specified. Third, four *additional model domains* and respective model requirements were defined in which the descriptive application models can be combined und further utilized. These novel model domains focus on (1) the process-centric combination of application models in multi-models as well as their utilization in (2) workflow management, (3) process simulation, (4) risk simulation and project controlling. The following paragraphs outline the domain focus and the data formats of the nine modeling domains defined in the first and second step:

- The domain of *Building Information Models (BIM)* focuses on the functional, geometrical and topological description of building elements and their composition. All BIM application models are based on the IFC standard (Liebich 2006)

- The domain of *Construction Site Models (CSM)* comprises site infrastructures, construction machinery and equipment as well as building materials. To represent construction site elements with geometrical, mechanical, economical and procedural properties new XML-based data schemas are under development based on the IFC and the EUROLISTE specifications (German equipment committee 2007).

- The domain of *Organization Models (ORM)* defines the organizational actors as well as their responsibilities and IT resources forming organization of a construction project. To exchange organizational information a XML format was development based on previous research on virtual organizations (Hilbert et al. 2010).

- The domain of *Specification Models (SPM)* subsumes various descriptions of the qualities of building products and processes. Most important specification models are the bills of quantities (BoQ) and the corresponding quantity take-offs (QTO). They are formalized in XML formats based on the German standard GAEB DA XML (GAEB 2009) and REB 23.003 (REB 2009).
- The domain of *Cost Models (COM)* comprises models that allocate monetary values to building products and processes. For the exchange of cost information in construction contracting and accounting again the GAEB DA XML and REB 23.003 as well as proprietary data formats are used.
- The domain of *Time Schedule Models (TSM)* represents concepts of common scheduling models such as activities, relations, resource loads and calendars. They are exchanged by data formats of commercial scheduling applications as well as a corresponding subset of the ifcXML specifications (Liebich 2011).
- The domain of *Risk Models (RIM)* comprises general risk catalogues and project-specific risk lists indicating possible events and measures that may critical or positive effects on the project performance. For the exchange of risk catalogues and lists a new XML-based format has been specified.
- The domains of *Stochastic Models (STM)* and *Fuzzy Models (FUM)* are used to explicitly quantify the risks as well as to represent uncertainties originating in the approximations made during model creation.

The specifications for the container and the application models are used in two ways to further describe the multi-models created throughout a project: First, the selected data schemas are modified to define variants of application models. In respect to the IDM methodology the derived data schemas are called *model view definitions* (ISO 29481-1). They specify a data format for application models that only represent a subset of all possible application models or that fulfill more rigorous modeling constraints while remaining valid models in respect to the original schema. Second, the application model schemas and corresponding view definitions are used to define *multi-model templates (MMTs)*. A multi-model template is represented by a container that holds meta-information but no actual model data. As illustrated in figure 1, right the meta-information is used to define templates for the contained elementary and link models indicating their anticipated content, scope, detailing and formalization.

2.3 Operations for multi-model creation and use

In order to create, exchange and reuse multi-models the software applications on the Mefisto platform have to implement model operations that are beyond today's standard software functionalities. Figure 2 illustrates the identified model operations by a use-case scenario, in which a multi-model is created by one project participant and further used by another.

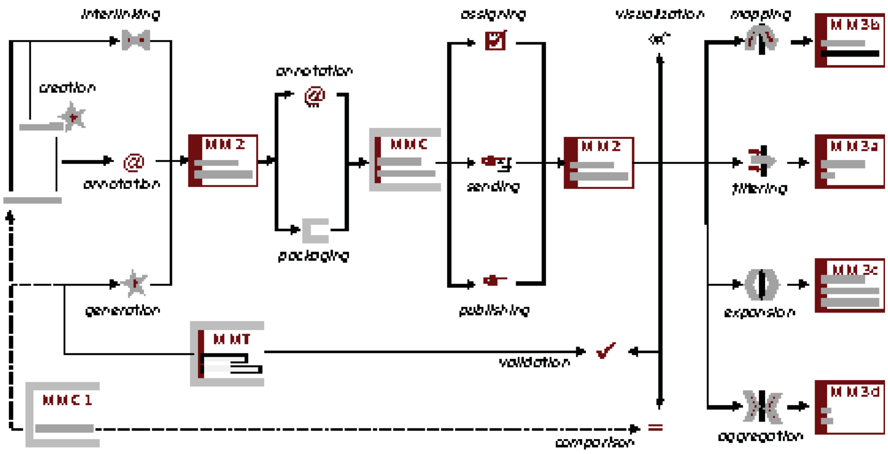

Fig. 2: Operations for multi-model creation and use

The scenario comprises four steps in which the multi-models are developed and exchanged as well as they are inspected and preprocessed to facilitate further reuse. Starting point of *multi-model development* is a multi-model template (MMT) that represents the information requirements for the new multi-model. The development of the multi-model may involve four operations. On the one hand a set of existing application models (cf. MM1) or newly created application models (*creation*) can be interlinked (*interlinking*). On the other hand rules can be used to automatically generate a new interlinked application model on the basis of existing ones (*generation*). All these operations can be supported by semantic annotations (*annotation)* as discussed in section 3.

For the *exchange of multi-models* the application and the link model are serialized in multi-model containers (*packaging*). Here they are complemented with meta-information indicating their content and development context (*annotation*). After that the multi-model container can be exchanged using standard communication technologies such as E-mail (*sending*) as well as it can be registered on the Mefisto platform with its meta-information (*publishing*). Moreover, the multi-model can be forwarded to another project participant in the course of assigning a workflow task (*assigning*) (Schapke and Fuchs 2011).

For the *inspection of a received multi-model* a variety of validation and visualization techniques can be applied. First, the content of a multi-model can be validated against the schemas of application model formats and corresponding view definitions (*validation*). Moreover, comparisons can be made with related application models representing more abstract plans and older versions from earlier project phases (*comparison*). Second, as discussed in Tauscher et al. (2011), novel visualization techniques are explored to browse the content of a multi-model and illustrate the interdependencies among contained application models (*visualization*).

Most important for the effective utilization of multi-models are the functionalities to *automatically preprocess* the application models of a container. The heterogeneity of application models often requires mappings technologies that allow for the transformation of engineering and management information the internal data structures (*mapping*). Moreover, pre-defined multi-model filters are provided that allow for extracting the project information that is required for certain planning or analyses tasks from the application models (*filtering*). Finally, novel methods are developed to specifically support the detailing of certain application models in the course of project planning (*expansion*) as well as the automatic aggregation of model-based information to calculate and visualize performance indicators for overall project phases, building sections and work packages (*aggregation*).

3. Ontology-Based Multi-Model Annotations

The presented multi-model specifications and modeling methods provide for a flexible utilization of application models on a construction project. However, the varying focus, structure and semantic aggravate the integration and analyses of the models. Hence, a *layered ontology framework* was developed to support the uniform denotation and organization of project information. The basic concepts of the framework are depicted in figure 3.

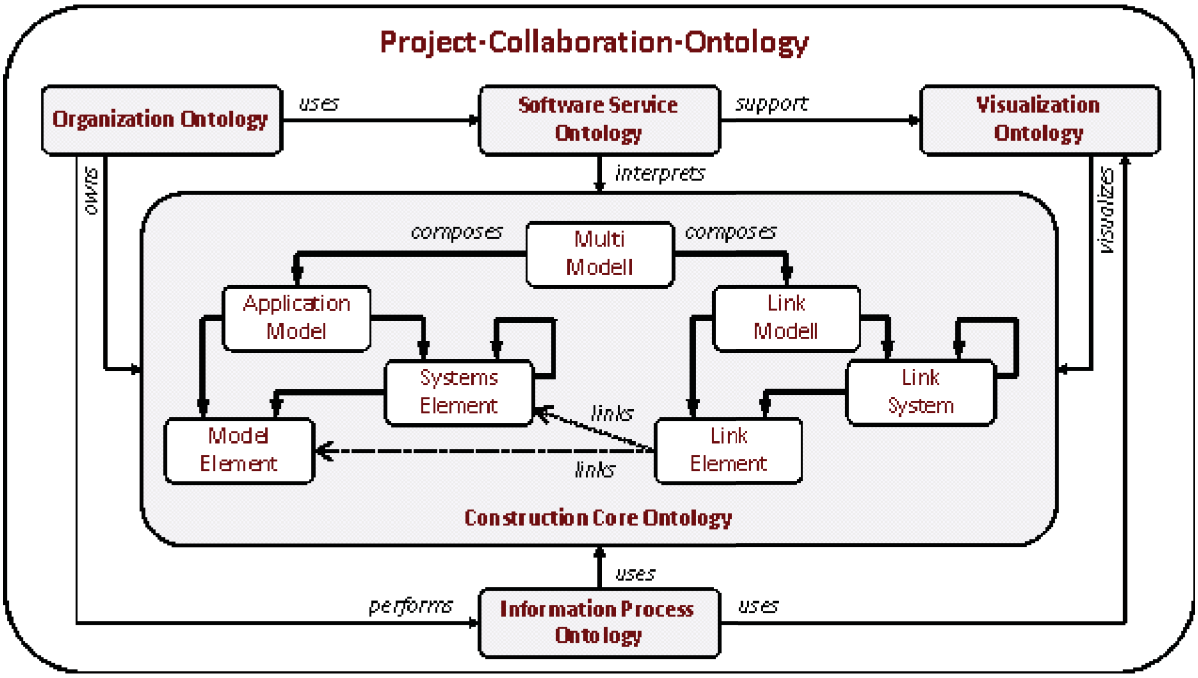

Fig. 3: Layered ontology framework

In regard to different application areas the concepts of the ontology framework are structured into two intersecting application ontologies, namely the Construction Core Ontology depicted by the center rectangle and the Project Collaboration Ontology depicted by the outer rectangle in figure 3.

3.1 Construction Core Ontology

The Construction Core Ontology represents the concepts that are needed to classify the content of a multi-model. It is intended to complement the existing data specifications. On the one hand it defines the semantics for knowledge bases to support the creation and inter-linking of application models. First, it provides for the uniform annotation of application model elements in various domains. Second, additional integrity constraints and rules can be specified with the ontology to validate the technical content of the models and deduce supplementing project information. On the other hand, the Construction Core Ontology shall also allow for classifying the overall application models and corresponding multi-models to support the management of the distributed multi-models based the Project Collaboration Ontology as described in section 3.2.

The Construction Core Ontology is organized on two layers. The upper layer specifies the generic concepts of a multi-model that can be further specialized for different modeling domains on the lower application layer. Figure 3 depicts the concepts of the *upper layer*: Within the application models it distinguishes between basic elements and systems elements. The *systems elements* are introduced to allow for the indication of different engineering systems that are combined within some application models (Scherer and Schapke 2011). They represent compositions of multiple basic or systems elements. These compositions act as single elements and exhibit features in addition to those of the composed elements. Respectively, *basic elements* are defined as elements that are not further decomposed within a given application area. Comparably, the link models first comprise the link elements interlinking a number of *n* basic or systems elements from *m* models. In correspondence to the application models, the link elements can be grouped by *link systems*. In addition to organizing the link elements, such link systems may indicate the engineering and management systems composed of elements from multiple application models. Finally, a multi-model is defined as a collection of application and link models.

On the *application layer* the model elements and systems as well as the application models and multi-models can be differentiated in poly-hierarchic classifications in respect to different application domains, project phase, levels of detail and subject matters as described in section 4.

3.2 Project Collaboration Ontology

The Project Collaboration Ontology defines a semantic vocabulary to realize the information logistics of multi-models on the Mefisto platform (Scherer and Schapke 2011. It specifies the types of collaboration processes for creation and use of the multi-models as well as the respective project participants and their software applications. Overall, it is structured into five sub-ontologies:

- First, to describe the content of the multi-models the Project Collaboration Ontology integrates the classifications of application, link and multi-models from *Construction Core Ontology*.
- Second, to support the visualization of multi-models, a *Multi-model Visualization Ontology* is developed that supports identification and automatic generation of information visualizations, in respect to the content of a multi-model and the context of the user.
- Third, the *Software Service Ontology* provides for the denotation of platform services. In addition to network addresses and service profiles, it indicates the data formats and model operations supported by the services.
- Fourth, the *Organization Ontology* provides for the classification the platform users as well as for the roles-based specification of their project responsibilities.
- Finally, the *Information Process Ontology* binds together the presented domain ontologies. The ontology schema provides the basis for the definition the collaboration processes for multi-model creation and use that can be executed as workflows on the platform.

4. Defining Semantic Annotation Vocabularies

The Construction Core and the Project Collaboration Ontology define semantic vocabularies for the uniform denotation of construction products, actors, processes and resources throughout different application domains. On the Mefisto platform they are first of all used to explicitly specify the vocabularies to annotate multi-models on a given construction project. In a second step these vocabularies shall be complemented with integrity constraints and rules for the automatic classification of elements and validation of element compositions.

To allow for an efficient configuration of the ontologies for different construction projects taxonomic inheritance hierarchies are build based on existing semantic resources such as technical vocabularies and classification systems. A wide variety of general metadata schemas and nomenclatures have been developed in information science as well as there are numerous classification systems for different industry sectors. From an international perspective most important for the AEC/FM industry are the facetted construction classification systems based on the ISO 12006-2 such as OmniClass (OmniClass 2006). Moreover, numerous national classifications exist defining the technical terms to specify construction products and processes as well as the legal terms to regulate the rights and liabilities of the respective project participants.

The following two sections outline our approach to use the exiting vocabularies to further specialize the core concepts of the ontologies. Section 4.1 discusses the base vocabularies that have been developed to annotate application models in multi-model containers. Section 4.2 presents a method and a first software prototype to configure ontologies combining multiple base vocabularies.

4.1 Base vocabularies for application models

Starting point for defining the Construction Core Ontology are the metadata vocabularies that have been used in preliminary scenario analyses to describe different application models. The scenario analyses examined the possible use of multi-models at the owner and the contractor organizations throughout the project phases from project bidding to construction execution. They were conducted based on the Process Matrix methodology (Wix et al. 2002) and the Information Delivery Manuals (ISO 29481-1) and the identified processes for multi-model creation and reuse were documented in a newly defined Scenario Matrix (Scherer & Schapke 2010). Within the Scenario Matrix the required input information as well as the resulting output information of a planning or controlling task is represented by a set of application models that are described using the metadata attributes depicted in the following notation.

$$\left({}_{project}phase\ p^{status\ s}\ \ \textbf{Model Name}\ \ {}^{subject\ matter\ m,\ level\ of\ detail\ l}_{model\ domain\ d,\ data\ format\ f}\right.$$

While the *names* of the application models were freely chosen, the following controlled vocabularies were developed for the metadata attributes indicated by the indices.

Model domain and data format: The application model domains and data formats were identified as described in section 2.2 and consolidated in two vocabularies. The *taxonomy of model domains* classifies the descriptive application models in: (1) models of physical construction products and resources, i.e. BIM, CSM, ORM, (2) models of concepts for construction coordination and management, i.e. SPM, COM, TSM or (3) models of concepts for risks and uncertainties, i.e. RIM, STM, FUM (Scherer and Schapke 2011). Second, these model domains are sub-structured to represent typical subsets or systems within the respective application models. For example, the different building models utilized in the scenario analysis for a high-rise office building are composed of spatial elements, structural building elements as well as of building façade elements. Based on the model domains the *vocabulary of data formats* was defined compiling a simple list of applicable data formats by their internet media type and file extension (W3C 2002).

Subject matter: While the application models of a certain domain are based on the same concepts to represent geometrical, physical, monetary or organizational aspects they are not necessarily concerned with the same topic or subject matter. For example, given today's scheduling formats it is possible to distinguish project plans defined as simple project networks or precedence diagrams including or excluding resources, but it remains difficult to detect, whether they comprise construction planning or execution tasks. Hence, a polyhierarchic classification of subject matters was developed based on the classification system of the German standard DIN 276 (DIN 276). The standard originally specifies methods and structures to be used for cost estimating on public construction projects in Germany. Considering project costs for the planning, the management and the production of buildings as well as their interior and exterior facilities it covers a wide variety of construction management aspects. However, to address the subject matters of all application models identified in the scenario analyses the classification has been complemented and slightly restructured. In addition to distinguishing costs – or respectively subjects – regarding the site, the structure, the technical systems and the furnishings of a building two subject classifications concerned with the spatial systems as well as the construction site infrastructure were defined. Moreover, as depicted in figure 4 the original classification of building structure element (i.e. cost group 300) were also differentiated to whether they belong to the load bearing structure, the interior build-out or the exterior enclosure.

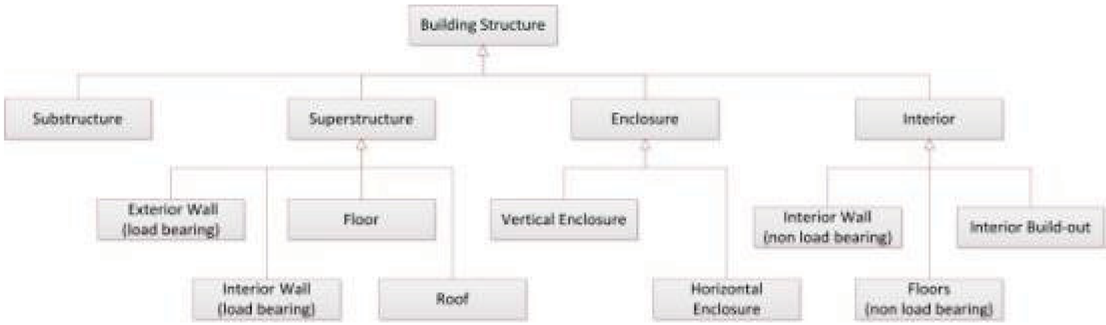

Fig. 4: Classification of subject matters in the field of construction works

Level of details: The metadata attribute 'level of detail' (LoD) indicates in which detail the elements of an application model are specified. The vocabulary of LoDs was defined based on the established ordinal scale of CityGML (Kolbe et al. 2006). This scale distinguishes five levels of details: LoD 0 – regional, landscape, LoD1 – city, region, LoD2 – city districts, projects, LoD3 – architectural models (outside), landmarks und LoD4 – architectural models (interior). Nagel und Häfele (Nagel and Häfele 2007) have demonstrated how these levels of details can be interpreted in the domain of building information models. On the Mefisto platform this reference to the geometrical building and its environment has also been transferred to application models of other domains. Hence, the LoD an application model such as a schedule or a bill of quantities is determined by the detailing of the building elements that are referenced by a single activity or line item. To more accurately indicate the levels of detail of the identified application models the five LoDs of CityGML were complemented by a sixth level for those models that comprise detailed descriptions of building element components. Furthermore, each of the LoD classes was structured into two subclasses, which were described for the different model domains.

Project phase: The metadata attribute 'project phase' is used to specify the project phase in which an application model was created. Throughout different countries, numerous models exist for phasing construction projects. However, they often represent simple models that do not identify the different phases from the owners' as well as from the contractors' perspective. In the Mefisto project the classification of project phases was developed structuring the processes of the scenario analyses in accordance to the corporate organizations of the industry partners. On the first three hierarchy levels it also reflects the German regulations of the HOAI (HOAI 2004) that structures the duties of architects and engineers in nine project phases, indicated by the circled boxes.

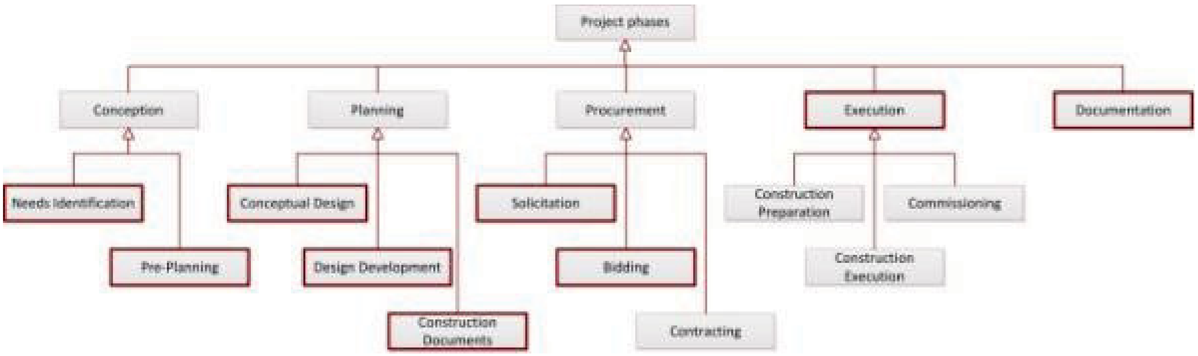

Fig. 5: Classification of project phases

Status: The metadata attribute 'status' is used to define the current editing status of an application model. For the vocabulary of models status a simple ordinal scale was formulated. It distinguishes (α) model requests and templates, (β) model drafts, (γ) accepted/ released models and (ε) deprecated and rejected models.

4.2 Ontology Configurator

For the configuration of ontologies from existing metadata vocabularies an Ontology Configurator is developed. It allows for the generation of polyhierarchic taxonomies from a given set of classification systems. Figure 6 illustrates the specialization method in principle automatically generating six classes of application models based on the combination of two simple vocabularies of application model domains (BIM and TSM) and subject matters concerning different work areas of the building structure (Superstructure, Enclosure, Interior).

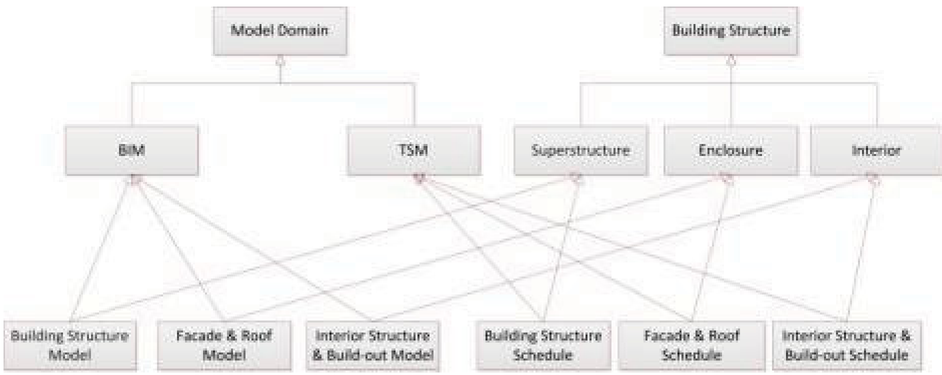

Fig. 6: Polyhierarchic taxonomy of building models and schedules for different construction work areas

The overall process for ontology configuration comprises five steps: In the first step existing classifications focusing on single facets are imported or manually entered. The respective classes are called *base classes*. Second, subclasses are generated for all possible combinations of base classes from different classifications. In a third step these *extended classes* are further configured by the user. In a fourth step the base and the extended classes can be described in more detail specifying additional attributes to be inherited by all subclasses. Finally, complementary rules and restrictions concerning the possible combinations of classes can be specified in a fifth step.

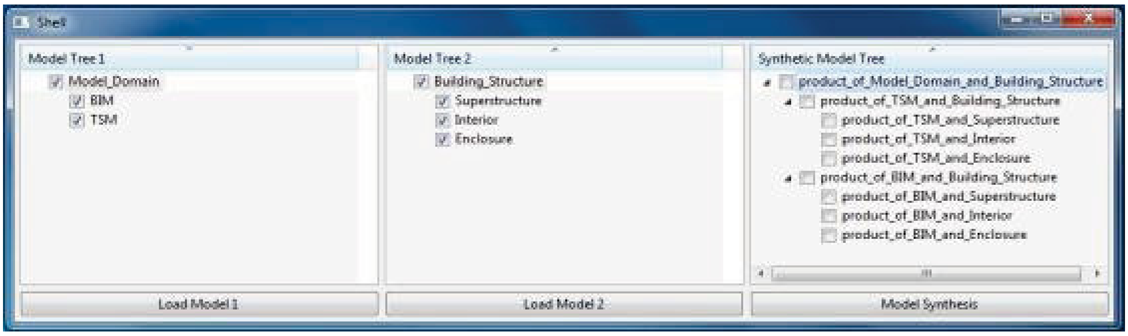

Fig. 7: User interface of the Ontology Configurator

Figure 7 shows a first user interface of the Ontology Configurator. It comprises three display areas: The left and the centre areas depict the imported classifications or vocabularies and the right area the polyhierarchic classification generated by their combination. To offer a common and widespread exchange format the input classifications are read as OWL-documents. During the import process existing polyhierarchical structures are reduced to monohierarchies for a simplified planar graphical representation. The actual synthesis process combines the selected classes of the input classifications without violating the predefined inheritance relationships. The results of this process are again represented in a monohierarchical graphical form and stored as OWL-documents.

5. Conclusion

The paper presents methods and technologies for the creation and utilization of multi-models. In particular it discusses the use of semantic annotations based on a layered ontology framework. In addition to the general structure of the ontology framework a novel approach to configuring the respective ontologies for a construction project is introduced. To demonstrate the approach the use of metadata vocabularies and corresponding ontologies for the annotation of multi-models and the description of the project information space is discussed.

6. Acknowledgment

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