A parametric method for building design optimization based on Life Cycle Assessment

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Abstract

The building sector is responsible for a large share of human environmental impacts. Architects and planners are the key players for reducing the environmental impacts of buildings, as they define them to a large extent. *Life Cycle Assessment* (LCA) allows for the holistic environmental analysis of a building. However, it is currently not employed to improve the environmental performance of buildings during the design process, although the potential for optimization is greatest there. One main reason is the lack of an adequate means of applying LCA in the architectural design process. As such, the main objective of this thesis is to develop a method for environmental building design optimization that is applicable in the design process. The key concept proposed in this thesis is to combine LCA with parametric design, because it proved to have a high potential for design optimization. The research approach includes the analysis of the characteristics of LCA for buildings and the architectural design stages to identify the research gap, the establishment of a requirement catalogue, the development of a method based on a digital, parametric model, and an evaluation of the method.

An analysis of currently available approaches for LCA of buildings indicates that they are either holistic but very complex or simple but not holistic. Furthermore, none of them provide the opportunity for optimization in the architectural design process, which is the main research gap. The requirements derived from the analysis have been summarized in the form of a catalogue. This catalogue can be used to evaluate both existing approaches and potential methods developed in the future. In this thesis, it served as guideline for the development of the parametric method – *Parametric Life Cycle Assessment* (PLCA). The unique main feature of PLCA is that embodied and operational environmental impact are calculated together. In combination with the self-contained workflow of the method, this provides the basis for holistic, time-efficient environmental design optimization. The application of PLCA to three examples indicated that all established mandatory requirements are met. In all cases, environmental impact could be significantly reduced. In comparison to conventional approaches, PLCA was shown to be much more time-efficient.

PLCA allows architects to focus on their main task of designing the building, and finally makes LCA practically useful as one of several criteria for design optimization. With PLCA, the building design can be time-efficiently optimized from the beginning of the most influential early design stages, which has not been possible until now. PLCA provides a good starting point for further research. In the future, it could be extended by integrating the social and economic aspects of sustainability.

Kurzfassung

Der Bau und der Betrieb von Gebäuden sind weltweit für einen großen Teil an negativen Umweltwirkungen verantwortlich, zu denen unter anderem Energie- und Ressourcenverbrauch sowie Treibhausgas- und Schadstoffemissionen zählen. Die Ökobilanzierung (engl. Life Cycle Assessment, LCA) ermöglicht es, Gebäude ganzheitlich über den gesamten Lebenszyklus ökologisch zu bewerten. Allerdings wird sie aufgrund ihrer Komplexität zurzeit nicht zur Optimierung in der Planung angewendet, obwohl hier das größte Potential zur Reduktion von negativen Umweltwirkungen besteht. Ein wesentlicher Grund sind fehlende praktikable Methoden im architektonischen Entwurfsprozess. Daher bestand das Hauptziel der vorliegenden Arbeit in der Entwicklung einer Methode, die es ermöglicht, Gebäude im Entwurfsprozess zeiteffizient ökologisch zu optimieren. Dazu wurde der Stand der Technik zusammengefasst, ein Anforderungskatalog erstellt, eine entsprechende Methode entwickelt und diese wiederum praxisnah getestet und evaluiert. Der zentrale methodische Ansatz ist die neuartige Kombination der Ökobilanzierung mit dem parametrischen Entwerfen, da sich letzteres für die Optimierung von Gebäudeentwürfen als sehr geeignet erwies.

Die Analyse bestehender Ansätze für Gebäudeökobilanzierung zeigte, dass diese zwei maßgebliche Schwachstellen aufweisen. Einerseits sind ganzheitliche Ansätze zu komplex für die Anwendung im Entwurfsprozess, andererseits sind einfache Programme nicht ganzheitlich und damit ungeeignet. Darüber hinaus fehlte bis dato eine Methode zur zeiteffizienten Optimierung der Umweltwirkungen. Die Anforderungen, die sich aus der Analyse ergaben, wurden in einem Katalog zusammengefasst, der sowohl als Grundlage für die Entwicklung neuer Methoden als auch zur Bewertung bestehender Methoden dienen kann. Mit Hilfe dieses Katalogs wurde die parametrische Methode zur Ökobilanzierung entwickelt. Die Einzigartigkeit der Methode besteht in der Verknüpfung aller relevanten Aspekte, wie Energiebedarfsberechnung und Massenermittlung. Dadurch wird es möglich in einem geschlossenen Arbeitsablauf die Umweltwirkungen über den gesamten Lebenszyklus zu ermitteln, um eine Basis für effiziente, ganzheitliche Optimierung zu schaffen. In drei Anwendungsbeispielen konnte gezeigt werden, dass die parametrische Methode alle maßgeblichen Anforderungen erfüllt und die negativen Umweltwirkungen der Gebäudeentwürfe deutlich reduziert werden. Im Vergleich zu herkömmlichen Ansätzen ist die parametrische Methode zudem um ein Vielfaches schneller und liefert ganzheitliche Ergebnisse.

Mit Hilfe der hier entwickelten parametrischen Methode ist es erstmals möglich, Gebäude zeiteffizient und ganzheitlich im Entwurfsprozess ökologisch zu optimieren. Die in dieser Arbeit vorgestellten Ergebnisse bieten einen guten Ausgangspunkt, um in Zukunft weitere Aspekte der Nachhaltigkeit als Optimierungskriterien zu integrieren.

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Abbreviations

BOQ	Bill of quantities
CAALA	Computer-aided architectural life cycle assessment
EOL	End of life
EPD	Environmental Product Declaration
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LOD	Level of development
PCR	Product category rules
PLCA	Parametric life cycle assessment
RSL	Reference service life
RSP	Reference study period

Nomenclature used in equations

	Name	Unit
I	Environmental impact	-
ED	Energy demand	kWh
M	Mass	kg
R	Amount of replacements	-
RSP	Reference study period	a
RSL	Reference service life (of a building component)	a
IF	Environmental impact factor	-
PF	Performance factor of a building service	-
PET	Total primary energy	MJ
PERT	Total renewable primary energy	MJ
PENRT	Total non-renewable primary energy	MJ
GWP	Global Warming Potential for a time horizon of 100 years	kg CO_2-eqv.
EP	Eutrophication Potential	kg R11-eqv.
AP	Acidification Potential	kg SO_2-eqv.
ODP	Ozone Layer Depletion Potential	kg PO_4^{3-}-eqv.
POCP	Photochemical Ozone Creation Potential	kg C_2H_4-eqv.
ADPE	Abiotic Resource Depletion Potential for elements	kg Sb-eqv.

Subscript:

LC	Life Cycle
O	Operational
E	Embodied
heat	Heating
env	Building envelope
pri	Primary structure

Introduction

This preliminary chapter is divided into six parts and provides a brief introduction to the research background and the problem statement. Additionally, it describes the research objective, the research questions, the research approach, and the outline for this thesis.

a) Research background

The building sector is responsible for a large proportion of the world's consumption of energy and resources, and has a significant environmental impact. Approximately 50% of the world's processed raw materials are used for construction (Hegger et al. 2007, p.26). Buildings account for more than 40% of the world's primary energy demand and one third of greenhouse gas emissions (UNEP SBCI 2009, p.6).

To lower the energy demand of buildings, regulations on energy efficiency have been introduced in most industrial countries. These regulations have successfully reduced the operational energy demand and the resulting operational environmental impact of new buildings over the last 40 years (Hegger et al. 2012, p.2). As a result, the energy embodied in the production and disposal of buildings and the environmental impacts resulting from it have gained significance (see Figure 1). The embodied energy of a residential building to a *low energy standard* accounts for a share between 30% and 50% (El Khouli et al. 2014, p.32) of the whole life cycle primary energy demand. Beginning in 2021, the European Directive on Energy Performance of Buildings will require that all new buildings will be so-called *Nearly Zero Energy Buildings* (NZEB) with an operational energy demand close to zero (EU 2010, Article 9-1a). In consequence, the embodied energy will become even more significant.

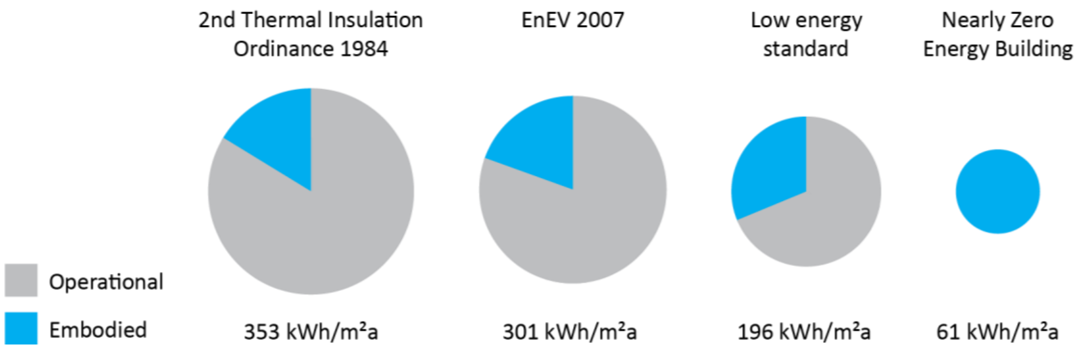

Figure 1: The proportion of operational and embodied energy in the primary energy demand of residential buildings in different German energy standards for a reference study period of 50 years (based on Hegger et al. 2012, p.2)

The embodied energy is also relevant for refurbishment of existing buildings. Europe has a large building stock with a high operational energy demand (Economidou et al. 2011, p.49). To meet the European goals on energy savings, a large number of existing buildings must be refurbished. State-of-the-art measures employ very high insulation thicknesses, highly insulated thermal windows, and mechanical ventilation, among other things. All of these measures require resources and energy, both for their production and again for their later disposal. Therefore, they all involve embodied energy and environmental impacts.

b) Problem statement

To further reduce the environmental impact of buildings, both operational and embodied impact have to be evaluated over the whole life cycle. Various approaches to evaluate the environmental impact of products and services exist, but Life Cycle Assessment (LCA) is the only internationally standardized method (Klöpffer & Grahl 2009, p.XI) and most prevalent in the scientific context. However, in general a significant gap between the application of LCA in theory and practice exists (Baitz et al. 2012, p.11). This is also true for the building sector, where LCA has become a widely accepted method in a scientific context, but is rarely applied in architectural practice. Building regulations require the evaluation of the operational energy demand, but do not consider the energy and resources needed for the production, refurbishment and dismantling of buildings (Szalay & Zöld 2007, p.1762). The evaluation of these aspects is voluntary. Only some building certification systems such as *DGNB*[1] and *BNB*[2] require an LCA.

In the few cases that an LCA is conducted in practice, it usually involves three participants in a cascaded workflow (see Figure 2). First, the architect designs the building and delivers the plans to an energy consultant. Second, the energy consultant calculates the operational energy demand. Third, the LCA practitioner receives the results for the operational energy demand and a bill of quantities (BOQ) from the architect and carries out the LCA. This current process for LCA of buildings in practice is discontinuous and inefficient. The energy consultant only focusses on the operational energy demand, while the LCA practitioner focusses on the embodied energy and embodied impact. The interrelation between the operational and embodied impact is lost. Trade-off effects cannot be considered, which can lead to suboptimal solutions. Furthermore, the current process requires a lot of manual,

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[1] The DGNB system is a German building certification system for private buildings provided by the German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen). See http://www.dgnb-system.de/en/system/certification_system/ (accessed March 1st 2016)

[2] Bewertungssystem Nachhaltiges Bauen (BNB) is a German building certification system for public buildings provided by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. See https://www.bnb-nachhaltigesbauen.de/bewertungssystem.html (accessed March 1st 2016)

time-consuming input. Deadlines in the architectural design process are short, making time-efficiency a critical aspect when introducing LCA into the design process. Currently, the LCA results provided at the end of the cascaded workflow only reach the architects days later. As a result, only one, or very few variants are calculated. However, evaluating the building design through LCA is not sufficient on its own, as it does not improve the design (Wittstock et al. 2009, p.4). In order to minimize environmental impacts, an optimization process is necessary.

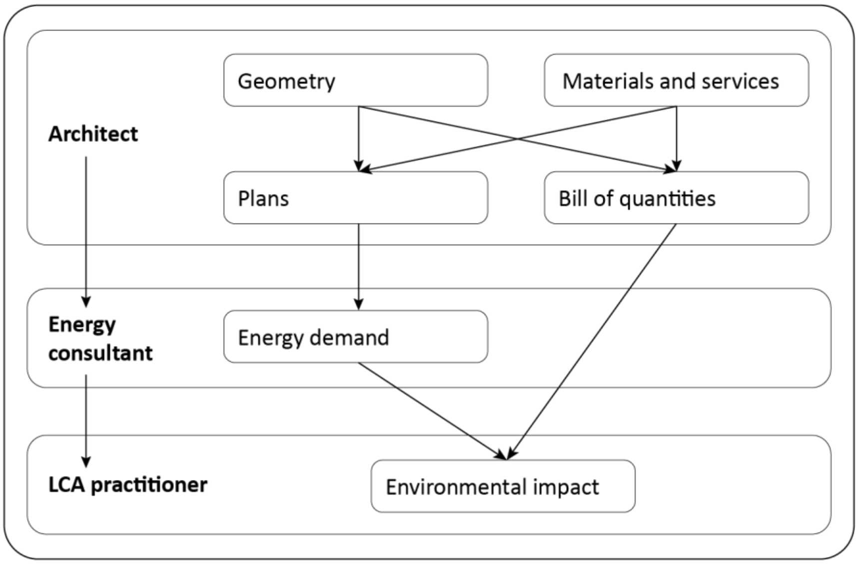

Figure 2: Conventional process for LCA in architectural design

In general, the greatest potential for design optimization is in the early stages (Paulson Jr. 1976, p.588). The detailed information typically required for LCA is only available in later design stages, but in those stages major changes to the design induce high costs. This leads to the dilemma that once the necessary information is available, the LCA results are difficult to implement (cf. Baitz et al. 2012, p.11). In consequence, the results of the LCA are not used to optimize the design.

The intricate calculation of LCA requires computational aid. However, currently available computational approaches for LCA for buildings are not adequate for application in architectural practice. They are either very detailed but too complex, or over-simplified and incapable of a holistic assessment. Furthermore, none of them provides the opportunity for design optimization.

In summary, the main problem is that LCA is not employed to improve the environmental performance of buildings. One main reason, amongst others, is the lack of adequate methods to apply LCA during the architectural design process. This problem can be divided into four sub-problems:

1. The state of the art of LCA approaches in architectural design and the current research gap are vague.
2. Requirements for environmental building design optimization methods have not been established.
3. The characteristics of a method for environmental building design optimization applicable in architectural design are unknown.
4. Such a method has not yet been tested and evaluated for application in the design process.

c) Research objectives

The main objective of this thesis is to provide architects and planners with a method for environmental building design optimization in the design process.

Architects and planners define the environmental impact of a building throughout its whole life cycle to a great extent. Architects are usually one of the first involved in the planning process of buildings and have the greatest influence in early design stages. In a short design phase of several months they define a large proportion of the environmental impacts a building will cause for the next fifty or hundred years. Therefore, they have the greatest opportunity to significantly reduce the environmental impact. Hence, this thesis focusses on providing architects with a method to time-efficiently reduce the environmental impact of a building design. Nevertheless, the method to be developed can be employed by all planners involved in the building design process alike. Whenever architects are referred to in the following, all planners are included.

The main objective is divided into four sub-objectives. The first sub-objective is to identify the specific research gap in environmental building design optimization methods. Therefore, the architectural design process and existing approaches for LCA of buildings are analysed in detail. Based on this analysis, requirements for environmental building design optimization methods are established, which is the second sub-objective. Because currently there is no adequate method available, the third sub-objective is to develop a method for environmental building design optimization that is applicable to the architectural design process, based on the established requirements. The fourth sub-objective is to apply the method in three case studies and evaluate it based on the established requirement catalogue. Furthermore, the resultant reduction in environmental impact and the time required will be assessed.

The anticipated result is a method which allows architects to time-efficiently reduce the environmental impact of a building design. This thesis provides the scientific basis for the method and explains its development, application, and evaluation. The method will be based on a digital, parametric model, and is therefore referred to as *Parametric Life Cycle Assessment* (PLCA). It will be designed to be applicable during all design stages, especially in the early design stages. Furthermore, it will be adaptable to the specific context of its application and equally suited to both new construction and the refurbishment of existing buildings. PLCA will be developed for residential buildings in a moderate, Western-European climate. Nevertheless, the same approach can be applied for all types of buildings worldwide, if the necessary information - such as climate, physical, and environmental data - is available.

PLCA will provide a possibility for architects to employ the LCA results as basis for decision-making and optimization in the design process. As such, the LCA results will become one important criterion for decision-making within other important architectural criteria, such as functionality and aesthetics. By significantly reducing the effort involved in conducting an LCA, the parametric method aims to allow architects to focus on their main task and main interest of designing the building.

d) Research questions

The main research question corresponding to the main objective described previously is:

> Which method enables architects to optimize a building for minimal environmental impact in the design process?

This research question can be divided into four sub-questions, which correspond to the four parts of the thesis.

1. Analysis: What are the main characteristics of LCA and the architectural design process as they pertain to the environmental optimization of buildings, and where is the research gap?
2. Requirements: Which requirements for environmental building design optimization methods can be derived from the analysis?
3. Development: What are the main characteristics of the parametric method?
4. Evaluation: Can the parametric method be employed for environmental optimization in architectural design, and which requirements are fulfilled?

Each part consists of further research questions. These individual questions and the relationships between them are shown in the research scheme in Figure 3.

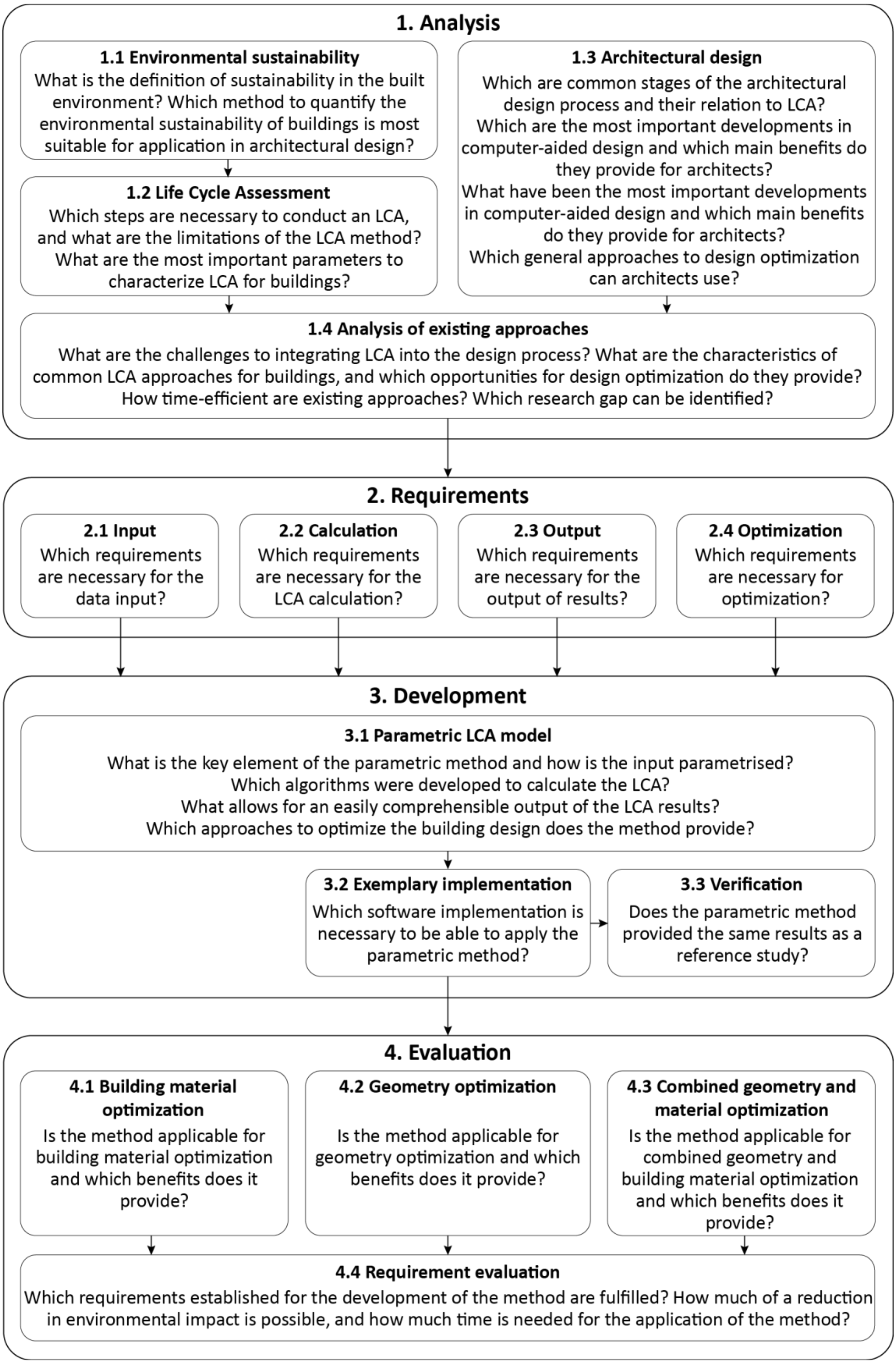

Figure 3: Research scheme

e) Research approach and methodology

The research approach consists of four main steps: analysis, requirements, development, and evaluation (see Figure 3). The first step begins with an analysis of the general LCA method and the specific characteristics of LCA for buildings based on a literature review. Furthermore, common stages of the architectural design process and their relation to LCA are analysed. The most common LCA approaches for buildings are surveyed in detail and evaluated for their applicability in the architectural design process. The analysis serves to identify a research gap.

In the second step, requirements for environmental building design optimization methods are defined based on the analysis of the first step. The requirements are structured according to the general workflow of computational analysis approaches: input, calculation, output, and optimization. A requirement catalogue is established, which serves as guideline for the development of the parametric method in step three.

Based on these requirements a parametric method for environmental building design optimization is developed in the third step. Optimization of building designs is based on generating, analysing, and comparing design variants. The use of computers has become an inherent part of architectural practice, and architects commonly use computer-aided design (CAD). The recent availability of suitable computer tools has promoted the application of parametric design in architecture (Davis 2013, p. 18). The parametric definition permits the effortless generation of many design variants. Hence, the parametric approach is ideal to generate variants for optimization. The key concept behind the method developed in this thesis is the combination of the principles of parametric design with LCA. The resulting parametric method is called *Parametric Life Cycle Assessment* (PLCA), and its core is a parametric LCA model. To allow for the automatization of the optimization process, all input data required for LCA is integrated and interlinked in the parametric LCA model. The entire process of calculating the LCA is described using algorithms. As such, variants for optimization can be generated either manually by the architect or by the computer. In order to be able to use PLCA, the parametric LCA model is implemented using parametric design software. An existing reference building was assessed to verify the algorithms developed for this thesis by comparing their results with a published study.

In the fourth step, PLCA is evaluated using three examples of application and the requirement catalogue. Three case studies, each consisting of a different scenario for environmental building design optimization, are described in detail. Based on the results of these case studies, an evaluation was performed to determine whether all requirements were fulfilled, how much of a reduction in environmental impact could be achieved, and how much time was needed for the application of PLCA.

f) Outline

The thesis consists of an introductory chapter, four main chapters corresponding to the four steps of the research approach (see Figure 3), and a concluding chapter. The answers to the four main research questions are provided in the summary at the end of each chapter. The answers to the detailed sub-research questions (see Figure 3) are provided in the summaries at the end of each section.

The first chapter introduces the scientific background for the proposed method and is divided into four parts. The first part of this chapter defines the term sustainability for the context of this thesis and provides an overview of methods to evaluate environmental sustainability. The second part analyses the general methodology of LCA and its application in the building sector. The third part provides an overview of the architectural design stages relevant to LCA and introduces approaches for design optimization. In the fourth part, existing approaches for LCA for buildings are evaluated with regard to their applicability in the architectural design process.

Based on the analysis in the first chapter and a literature review, requirements for environmental building design optimization methods are derived in the second chapter. The four parts of this chapter describe the requirements in terms of input, calculation, output and optimization. These requirements are summarized in a requirement catalogue.

The third chapter describes the development of a parametric method (PLCA) to reduce the environmental impact of a building during the design process. It consists of three parts. The first part describes the core of the method - a parametric LCA model. The algorithms employed and the workflow of the method are explained in detail. Furthermore, possibilities for design optimization based on the LCA results are provided. In the second part, implementation using parametric design software is described. The third part discusses the possibilities for verifying the results obtained from the implemented model by comparison to a published LCA study by Hartwig (2012).

Chapter four describes the application of PLCA for environmental building design optimization and evaluates the method. The first three parts of this chapter provide three application examples, each with a different focus. The first example focusses on the optimization of building materials in the case of refurbishment. The second one shows the application of PLCA for geometry optimization of a new residential building design. The third example describes the application of PLCA in a student design project for both geometric and building material optimization through manually comparing variants. In the fourth part, PLCA is evaluated based on the results of the application examples and the requirements established in the second chapter. Furthermore, the time-efficiency of PLCA is compared to existing methods.

1. Analysis

The building sector is responsible for a large share of total human environmental impacts (UNEP SBCI 2009, p.6). Different stakeholders, including energy consultants, building service experts, landlords, and facility managers have recognized the importance of reducing the environmental impacts of buildings. These stakeholders usually begin to be involved either in the detailed design stage or after the building has been constructed. Therefore, they can only influence the use phase of the building to a certain degree. In contrast, architects make decisions from the very beginning of planning, and define the building's geometry, orientation, and construction, as well as the choice of building materials, amongst other things. As such, they also influence the energy demand in the use phase and the potential for recycling materials at the end of their service life. In a short design phase of several months, they define the environmental impacts a building will have over the next fifty or one hundred years. Therefore, they are the key players in reducing the environmental impacts of buildings.

Evaluating the sustainability of buildings is often discussed in a qualitative manner, e.g. when juries decide in architectural competitions. The first quantitative sustainability rating, in the form of a building certification system, was launched in 1993 (Berardi 2012, p.416). The so-called second generation of these certification systems, with a mandatory, complete quantitative assessment of the building's life cycle was launched in 2008 (Ebert et al. 2011, p.26). *Life Cycle Assessment* (LCA) has been previously employed in scientific studies, e.g. Schuurmans-Stehmanna (1994, pp.712-716), Jönsson et al. (1998, pp. 218-223), Schmidt et al. (2004, pp.54-65), but not in architectural design practice. While energy demand calculation in the use phase of buildings has been common since the 1980s, the assessment of the whole life cycle of buildings in practice is relatively new. Environmental data for building materials have been commonly available for five to ten years and still need to be developed further (Passer et al. 2015, p.1211).

In order to apply LCA, a certain level of knowledge about the method and its particularities is needed. Therefore, this first chapter provides the scientific background for this thesis and analyses the state of the art of LCA for buildings and the architectural design stages. It is divided into four main sections: The first section defines the term *sustainability* for the context of this thesis and provides an overview of methods to evaluate environmental sustainability. The second section introduces the LCA method and the particularities of its application in the building sector. The third section describes the architectural design process and computational approaches in architectural design. In the fourth section, existing approaches to applying LCA during the architectural design process are analysed and evaluated. The key findings are summarized at the end of each of the four sections.

1.1. Environmental sustainability

The terms *sustainable* and *sustainability* are often used in different contexts of everyday life. A short overview of possible definitions is provided in the first part of this section in order to provide a common ground for this thesis. For an elaborate discussion of sustainability, see Kuhlman & Farrington (2010, pp.3436-3448). Different approaches to evaluate environmental sustainability are presented in the second part. Finally, the rationale for applying LCA in this thesis is summarized.

1.1.1. Definition of sustainability

According to Bahadir et al. (2000, p.797), the term *Nachhaltige Nutzung* (sustainable use) was first mentioned in *Sylvicultura oeconomica* by Hans Carl von Carlowitz (Carlowitz 1713, p.105), and referred to the sustainable use of forests. Driven by a scarcity of construction wood for mining, Carlowitz argued that each year only the amount of wood should be cut which grows back in one year in order to *sustain* the forest.

The most common definition of s*ustainable development* used today was given by the Brundtland Commission in the UN report *Our Common Future*:

> *„Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* (Brundtland Commission 1987, p.37).

The definition emphasizes human responsibility for the future. With the United Nations Conference on Environment and Development in Rio 1992, sustainable development became a global aspirational goal for economic and social development (Bahadir et al. 2000, p.797). Although being one of the most cited definitions, it is also criticized. Redclift (2005, p.213), for example, argues that needs themselves change over time. The needs of future generations will be different from ours today, and the needs of different cultures vary as well. This leads to the question of what should be sustained, which has not yet been agreed upon.

Elkington (1994, p.90) divided sustainability into three aspects - social, environmental, and economic – and coined the term *Triple Bottom Line.* This accounting framework is also known as the three Ps: *'people, planet and profit'*, and is typically illustrated using three circles (see Figure 4).

Based on the same concept, sustainability can be divided into three pillars: environmental, social, and economic sustainability (see Figure 5). Although Kuhlman & Farrington (2010, p.3437) call the distinction between the pillars "fuzzy", most sustainability standards in the building sector, e.g. EN 15643:2010, and certification systems such as BREEAM[3] or DGNB[4] incorporate this division into pillars.

The three circles or three pillars suggest each aspect of sustainability is equally important. However, Herman Daly's question "What use is a sawmill without a forest?" (cf. Daly & Cobb 1989) leads to the perspective that the economy is a subsystem of human society, which is itself a subsystem of the biosphere. Therefore, according to Daly, both economy and society are constrained by environmental limits and can only grow to this limit. Cato (2009, p.37) visualizes this hierarchy by embedding the circles of economy and society within the circle of the environment (see Figure 6).

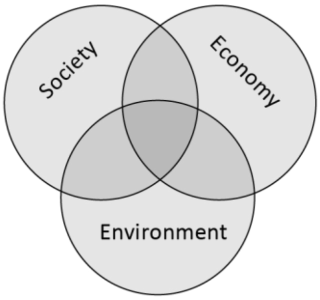

Figure 4: Three circles of sustainability

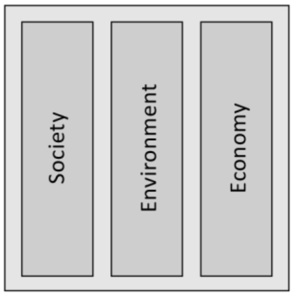

Figure 5: Three pillars of sustainability

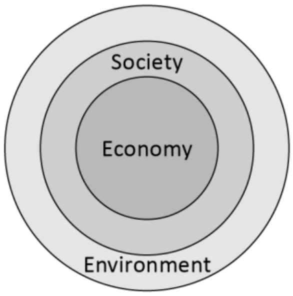

Figure 6: Nested sustainability (Cato 2009, p.37)

The United States Environmental Protection Agency provides the following definition:

> *"Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations."*
> US EPA (2015, p.1) based on the United States Executive Order 13514 (Federal Register 2009, Section 19)

[3] BREEAM (Building Research Establishment Environmental Assessment Methodology) was developed by Building Research Establishment and is worldwide the most commonly used building certification system.

[4] The DGNB system is a German building certification system for private buildings provided by the German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen). See http://www.dgnb-system.de/en/system/certification_system/ (accessed March 1st 2016)

This definition focusses on the environmental aspect of sustainability and emphasizes its importance, but does not neglect the social and economic aspect. Therefore, this definition suits the context of this thesis best.

1.1.2. Methods to evaluate the environmental sustainability

There are various environmental system analysis (ESA) tools for quantifying environmental sustainability. In Finnveden & Moberg (2005, p.1169), an overview of the most common ESA tools is provided, where they are categorized according to their suitability for the objects under study and impacts to be assessed (see Figure 7). In addition to the ESA tools described by Moberg, the concept of *Cradle to Cradle* and *Product Environmental Footprint* have been added, which have only recently been introduced for the built environment.

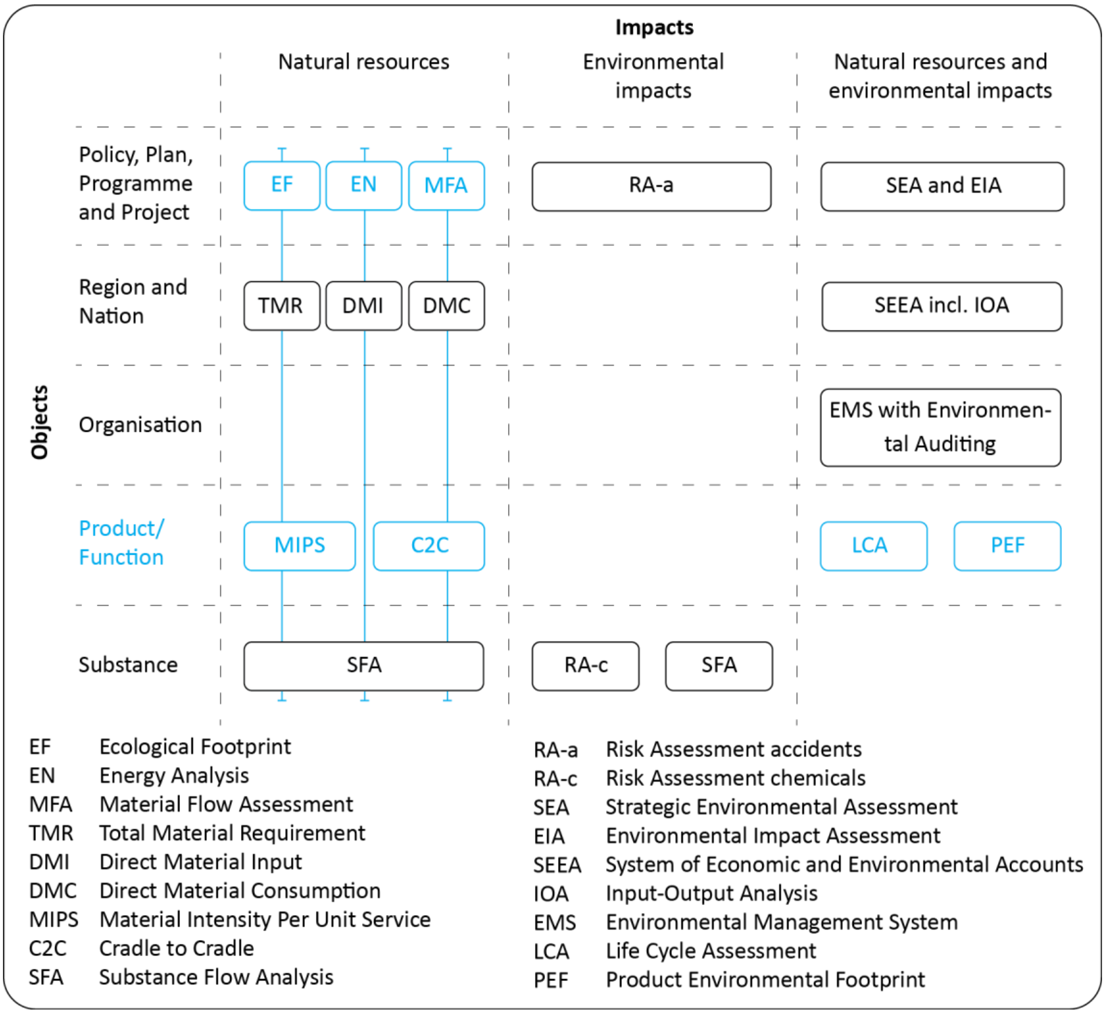

Figure 7: Overview of different ESA tools based on (Finnveden & Moberg 2005, p.1169)

For assessing buildings, only ESA tools for studying products are of interest in this thesis. These are briefly described and evaluated as follows.

Ecological footprint

The basic idea of the *ecological footprint* (EF) is to compare the world's bio-capacity with humanity's demand for natural services. The Global Footprint Network published a standard (Global Footprint Network 2009), and the calculation method is explained in Borucke et al. (2013, pp.518-533). The footprint can also be calculated for individual environmental aspects, such as the *carbon footprint* or *water footprint*. Emissions to the environment are not considered, which impedes a holistic analysis.

Energy Analysis

Energy Analysis (EN) focusses on the inputs of physical measures. Fay et al. (2000, pp.34-39) carry out an energy analysis for the whole life cycle of residential building and call this approach *Life-Cycle Energy Analysis* (LCEA). Other studies use different types of energy measures, such as exergy and emergy. While energy is never destroyed during processes, exergy is consumed in all real world processes as entropy is produced. *Exergy analysis* is often used to evaluate the quality of industrial processes (Finnveden & Östlund 1997, p.932). Sakulpipatsin et al. (2010, pp.94-98) describe the application of exergy analysis for a building. The *emergy analysis* is the measurement of all previous solar energy inputs that have been used in creating a service and can be utilized to account for the natural capital required to deliver services and products (Kharrazi et al. 2014, p.82). In contrast to *Life Cycle Assessment* (LCA), which assesses output to the environment, only inputs are accounted for in the various energy analyses.

Material flow analysis

Material flow analysis (MFA) is based on the economic *input-output analysis* developed by Wassily W. Leontief in the 1930s (cf. Leontief 1951). The input-output analysis describes and analyses the supply relationship between different economic sectors (Bahadir et al. 2000, p.599). Brunner & Rechberger (2004, p.3) define MFA as a systematic assessment of the flows and stocks of materials within a system defined in space and time. Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of processes.

Common systems for investigations by MFA are regions, factories, or farms (Brunner and Rechberger 2004, p.4). MFA can be employed for analysis of a building stock in a specific region, e.g. York (Barrett et al. 2002, pp.25-94), but is rarely used for the analysis of a single building.

MIPS

The abbreviation MIPS stands for *Material Input per Service unit* and is an elementary measure to estimate the environmental impacts of a product or service (Ritthoff et al. 2002, p.9). The concept is sometimes also called the *ecological backpack,* and was developed at the Wuppertal Institute in Germany in the 1990s. The basic idea is to analyse the material input within the whole life cycle of a product. The calculation of MIPS consists of seven steps, which are explained in Ritthoff et al. (2002, pp.16-33). To facilitate the calculation, factors for the material input intensity (MIT) in kg/kg for a range of common materials are provided on the website of the Wuppertal Institute[5]. These are divided into five categories:

- abiotic raw materials
- biotic raw materials
- earth movements in agriculture and silviculture (mechanical earth movement or erosion)
- water
- air

There has been an initiative to employ MIPS for building evaluation in Germany called MipsHAUS[6], but it has not been applied on a large scale. The availability of MIT factors for building materials is limited, making application in architectural design difficult. MIPS only considers the input-related environmental impact. Other ecological aspects and emissions to the environment are not considered. Therefore, it is not suited for a holistic analysis.

Cradle to Cradle

The vision of *cradle to cradle* (C2C) as an alternative to the conventional cradle to grave production was sketched by Walter R. Stahel in 1976[7] (cf. Stahel & Reday-Mulvey 1981). The idea became popular through the manifesto of the same name by William McDonough and Michael Braungart (2002). The basic idea of the concept is to distinguish between biosphere

[5] Wuppertal Institut, http://wupperinst.org/info/details/wi/a/s/ad/365/, accessed February 19th 2016

[6] mipsHAUS gGmbH, http://www.mipshaus.de/, accessed February 19th 2016

[7] Walter Stahel and Geneviève Reday-Mulvey sketched the vision of a circular economy in a report for the European Commission called “The Potential for Substituting Manpower for Energy”. In 1982 report was published as a book with the title “Jobs for Tomorrow, the Potential for Substituting Manpower for Energy”.

and technosphere. The aim is to disassemble a product at the end of its life and separate its components according to their sphere of origin to ensure complete recyclability. Ideally, this allows for recycling the components infinitely.

A small range of building materials are certified and can be accessed via the website of the Cradle to Cradle Products Innovation Institute[8]. The certification systems BREEAM-NL[9] and LEED[10] give credit for using certified products in the building. The certification neglects the use phase of products, which is the most important for some products, such as buildings. It is not a holistic analysis, and can therefore only be regarded as additional to an analysis of the whole life cycle.

Life Cycle Assessment

Life Cycle Assessment (LCA) involves the evaluation of the environmental aspects of a product or service throughout all stages of its life cycle. LCA can be defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2009, p.11). Inputs can be resources, energy, pre-products, or auxiliary materials. Outputs are typically waste, by-products, or emissions to the air, water, or earth. The most important characteristic of LCA is that results are always based on a functional unit (König et al. 2009, p.40). A further key characteristic is the definition of a system boundary representing the border between the technosphere and the environment. LCA has become a widespread method of assessing the environmental impact of products and services. Originally, in the 1970s, LCA was developed for packaging products (cf. Boustead 1996, p.147; Ayres 1995, p.200; Klöpffer & Grahl 2014, p.7). In the last ten years it has also increasingly been applied for the evaluation of buildings, especially in an academic context (Weißenberger et al. 2014, p.552).

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[8] Cradle to Cradle Products Innovation Institute, http://www.c2ccertified.org/products/registry (accessed February 19th 2016)

[9] BREEAM-NL is the Dutch version of BREEAM provided by the Dutch Green Building Council, see https://www.breeam.nl (accessed March 1st 2016)

[10] LEED stands for Leadership in Energy and Environmental Design and is a building certification system provided by the U.S. Green Building Council, see http://www.usgbc.org/leed (accessed March 1st 2016)

Product Environmental Footprint

The ecological footprint described previously is not to be confused with the *Product Environmental Footprint* (PEF). The Institute for Environment and Sustainability of the European Commission defines PEF as a multi-criteria measure of the environmental performance of a good or service throughout its life cycle (Manfredi et al. 2012, p.1). Thus, in contrast to the ecological footprint, it considers emissions to the environment. PEF refers to ISO 14040:2009 and ISO 14044:2006, and can therefore be seen as a specific kind of LCA. Currently, PEF is being tested for various products in a pilot phase until 2016. Thermal insulation is the only building material currently being considered[11]. As the name indicates, the method focusses on products, and PEF has not been applied to whole buildings.

The characteristics of these different methods for evaluating environmental sustainability are summarized in Table 1.

Table 1: Characteristics of methods to evaluate environmental sustainability

	Production phase	Use Phase	End-of-life	Inputs	Outputs	Standardization	Data availability for building products	Integration in building certifica-tion systems
EF	✓			✓				
EN	✓	✓	✓	✓			✓	
MFA	✓	✓	✓	✓				
MIPS	✓			✓			(✓)	
C2C	✓		✓	✓	✓		(✓)*	BREEAM-NL^{O}, LEED^{O}
LCA	✓	✓	✓	✓	✓	✓	✓	DGNB^{M}, BNB^{M}, BREEAM^{O}, LEED^{O}
PEF	✓		✓	✓	✓	(✓)*		

✓ Criterion fulfilled — ^{M} Mandatory — * Under development
(✓) Criterion partially fulfilled — ^{O} Optional

[11] The product pilots including thermal insulation can be accessed on the website of the European Commission: http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm (accessed March 1st 2016)

It can be seen that only LCA covers all life cycle phases, as well as both inputs and outputs to the environment. The reasons for using LCA for the evaluation of the environmental sustainability of buildings in this thesis are listed below:

1. LCA considers the whole life cycle. Furthermore, it is a holistic analysis, considering both input from the environment and output to the environment, such as emissions or waste.
2. The consideration of the whole life cycle avoids ‘problem shifting’, which refers to solving one environmental problem by shifting it to another life cycle stage. For instance, manufacturing a car out of aluminium instead of steel reduces the weight and gasoline consumption in the use phase. However, the production of aluminium requires more energy. Whether a car made of aluminium or steel is more environmentally friendly can therefore only be judged when taking all these facts into account (Guinée et al. 2001, p.4).
3. LCA is the only international standardized method for quantifying environmental sustainability (Klöpffer & Grahl 2009, p.XI). The European framework to evaluate the sustainability of buildings EN 15643-1:2010 employs LCA to assess the environmental performance. The development of LCA is advanced, and standards for its application in the building sector exist, such as EN 15804:2012 and EN 15978:2012.
4. LCA is employed by building certification systems. For DGNB and BNB, LCA of the whole-building is mandatory and an important part of the certification. In LEED and BREEAM, LCA is an option to obtain extra credits for certification.
5. In contrast to MIPS or C2C, there are a range of international LCA data sources (see Section 1.2.2.4.), which include many different building materials. Data on all typical building materials is available. Furthermore, a lot of international data sources exist, allowing for the application of LCA in many different countries.

LCA methodology is described in Section 1.2.

1.1.3. Summary of Section 1.1

What is the definition of sustainability in the built environment?

Most sustainability standards in the building sector, such as EN 15643-1:2010, and most building certification systems, such as BREEAM or DGNB, consider sustainability in terms of three aspects: environmental, social, and economic sustainability. This thesis focusses on the environmental aspect of sustainability. Therefore, the definition of the United States Environmental Protection Agency, which emphasizes the importance of the environmental aspect suits the context of this thesis best:

> *"Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations."*
> US EPA (2015, p.1) based on the United States Executive Order 13514 (Federal Register 2009, Section 19)

Which method to quantify the environmental sustainability of buildings is most suitable for application in architectural design?

A brief evaluation of common methods to quantify environmental sustainability, including *Ecological footprint, Energy Analysis, Material Flow Analysis*, *Material Input per Service unit*, *Cradle to Cradle, Life Cycle Assessment* (LCA), and *Product Environmental Footprint* (PEF), shows that LCA is currently the most suitable for application in architectural design. The reasons for this, amongst others, are:

- LCA is the only international standardized method for quantifying environmental sustainability (Klöpffer & Grahl 2009, p.XI);
- standards for its application in the building sector exist;
- LCA considers inputs, outputs and the potential environmental impacts of a building throughout its whole life cycle;
- there are a range of international LCA data sources;
- LCA is employed by building certification systems.

Therefore, in this thesis, LCA is employed to evaluate the environmental sustainability of buildings.

1.2. Life Cycle Assessment

The general concept of LCA is simple, but the details of the application of the method are very complex. A range of assumptions are necessary which are not uniformly standardized, such as the system boundaries, or environmental indicators. To introduce the necessary background on LCA, the first part of this section introduces the basic concept of the LCA method based on ISO 14040:2009 and ISO 14044:2006. A more detailed description of LCA can be found in *Life Cycle Assessment (LCA) – A Guide to Best Practice* by Klöpffer & Grahl (2014). This compendium serves as one main source for the first part. The second part provides an overview of regulations and particularities of the application of LCA for buildings.

1.2.1. General LCA methodology

In addition to covering the whole life cycle of a product (see definition of LCA in Section 1.1.2), another important characteristic of LCA is that the results are always based on a functional unit (König et al. 2009, p.40). A further key characteristic is the definition of a system boundary representing the border between the technosphere and the environment. In the building sector, LCA is mostly applied to compare different building designs or building materials, which is called attributional LCA. In contrast, consequential LCA aims to assess the whole building sector, or the influence of a policy on it (Wittstock et al. 2012, p.13).

ISO 14040:2009 divides the process of LCA into four stages (see Figure 8), which are described as follows:

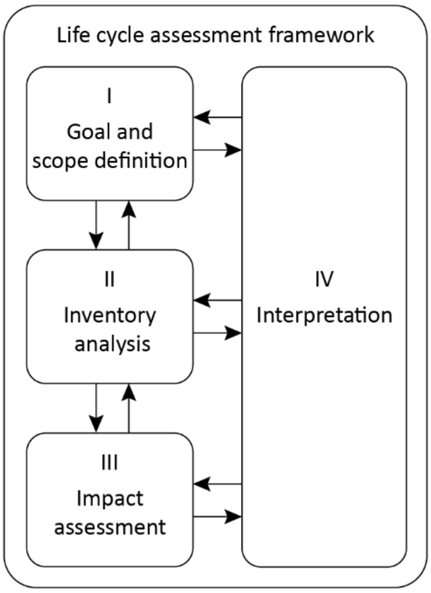

Figure 8: Stages of an LCA (based on ISO 14040:2009, p.16)

1.2.1.1. Goal and scope definition

In the first stage, the goal of an LCA states the intended application and the reasons for carrying out the study. The scope of the LCA further defines the level of detail, and should include the functional unit, system boundaries, impact categories, characterization models, and assumptions (ISO 14040:2009, pp.22-23).

ISO 14044 defines the functional unit as the “quantified performance of a product system for use as a reference unit” (ISO 14044:2006, p.15). As noted previously, this is crucial when comparing different products or services. First of all, it defines which functions of a product should be compared. For example, wood fibre insulation boards (WFIB) might be applied for thermal insulation or for impact noise insulation. For comparing WFIB to thermal insulation made of expanded polystyrene (EPS), the desired function is the thermal resistance. The functional unit could be 1 m^2 of insulation with a specific thermal resistance, for example. Comparisons without relation to a function, such as 1 kg WFIB vs. 1 kg of EPS, are not meaningful.

The functional unit also allows for comparison of products with services. ISO 14040 gives the example of the function ‘drying hands’ in order to compare paper towels and an air-dryer system. The reference flows are the mass of the paper towels and the volume of hot air needed on average to dry one pair of hands (ISO 14040:2009, p.24).

The system boundary is the border between the technosphere and the natural environment, and defines the unit processes to be included in the system. For building materials, for example, the usual system boundary is called *cradle-to-gate*, meaning all processes until the factory’s gate, e.g. raw material extraction, transportation, and production, are included. Ideally, the system boundary would always be defined *cradle-to-grave*. All inputs and outputs at the boundary would then be elementary flows.

Additionally, cut-off criteria have to be chosen and documented to further define the system boundaries. Assessing an air-dryer might lead to assessing the coating of the machine, then the factory where the coat was produced, the tyres of the truck which transported the coating and would end up assessing the whole world (cf. Klöpffer & Grahl 2009, p.4). Therefore, only significant processes should be included. The significance is defined by a certain percentage contribution of the individual product to the whole system, typically measured in mass, energy, or environmental impact. For building products, the cut-off criteria are defined in the *product category rules* (PCR) of EN 15804:2012. The PCR state that inputs with less than a 1% contribution to the mass or primary energy demand can be neglected, but the cumulative total of all of these neglected inputs should not exceed 5%. Neglected output should also contribute less than 1% to the emissions to the environment.

1.2.1.2. Life cycle inventory analysis

The aim of the *life cycle inventory analysis* (LCI) is to quantify the relevant inputs and outputs of a product system. Usually, this is the most resource-intensive stage, and is an iterative process (Klöpffer & Grahl 2009, p.63). Data for each unit process within the systems boundary is collected and can be classified as input or output:

- Inputs: Energy and raw-material input, ancillary inputs, other physical inputs
- Outputs: Products, co-products and waste; emissions to air, discharges to water and soil; other environmental aspects

Ideally, a sensitivity study is carried out to validate the initial cut-off criteria. In some cases, the system process must be modified and the LCI refined.

Most industrial processes have more than one product as output. Then the input and output have to be apportioned between the product under study and others. This process is called *allocation*. According to ISO 14044:2006, allocation should be avoided where possible by expanding the product system (ISO 14044:2006, p.28). If allocation cannot be avoided, the inputs and outputs should be apportioned according to their physical relation. If this is not possible, they can also be apportioned according to the economic value of the products.

1.2.1.3. Life cycle impact assessment

The *life cycle impact assessment* (LCIA) summarizes the results of the LCI according to their impact on the environment. This stage is divided into three mandatory steps:

1. Selection of impact categories, category indicators, and characterization models
2. Classification: Assigning the LCI results to impact categories
3. Characterization: Calculation of the category indicator results

In addition, ISO 14040:2009 lists three optional steps:

4. Normalization: Calculation of the magnitude of category indicator results relative to a reference
5. Grouping: Sorting and ranking of impact categories
6. Weighting: Multiplication of indicator results by value-based factors and possibly aggregation into a single point indicator

Various impact assessment methods, each consisting of a set of impact categories, have been developed in the past (see Table 2).

Table 2: Overview of impact assessment methods, based on JRC European Commission (2010a, p. 11) and Hildebrand (2014, p. 62)

Impact assessment method	Institute	Country
CML-2001	Institute of Environmental Sciences, Leiden University	Netherlands
Eco-Indicator 99	Pré Consultants	Netherlands
EDIP 2003	Institute for Product Development (IPU), Technical University of Denmark	Denmark
ReCiPe	RIVM, CML, Pré Consultants, Radboud Universiteit Nijmegen and CE Delft	Netherlands
LIME	National Institute of Advanced Industrial Science and Technology (AIST)	Japan
EPS 2000	Swedish Environmental Research Institute (IVL)	Sweden
Ecological Scarcity Method	Federal Office for the Environment (FOEN)	Switzerland
TRACI	U.S. Environmental Protection Agency	USA

Each impact assessment method employs various impact categories. The impact categories address different *environmental problem fields*. Various lists of environmental problem fields exist, which aim to cover the most acknowledged problems with the smallest overlap possible (Klöpffer & Grahl 2014, p.202). One of the early lists, which is still used in a similar manner today, is provided by SETAC Europe (Udo de Haes 1996, p.19) (see Table 3).

Table 3: List of environmental problem fields Klöpffer & Grahl (2014, p.204) after Udo de Haes (1996, p.19)

Input related	Output related
Abiotic resources	Global Warming / Climate Change
Biotic resources	Depletion of stratospheric ozone
Land	Human toxological impact
	Ecotoxological impact
	Photo-oxidant formation
	Acidification
	Eutrophication
	Odour*
	Noise
	Radiation
	Casualties*

*Proposed without operationalisation method

According to Klöpffer & Grahl (2014, p.206), four more possible environmental problem fields have emerged and are currently discussed in the scientific context:

- Hormone disrupters
- Possible harmful impacts of genetically modified organisms on the environment
- Invasive species
- Fresh water as a regionally scarce resource

For most environmental problem fields, methods to classify and characterize the LCI data into impact categories have been developed. Each impact category corresponds to a specific category indicator, characterization model, and characterization factor. To clarify the relation between these terms, an example for the impact category *climate change* is given. The impact assessment method CML-2001[12] uses the 100-year baseline model from the Intergovernmental Panel on Climate Change (IPCC 2007, p.212) as a characterization model. The corresponding category indicator is *infrared radiative force* and the characterization factor *Global Warming Potential* (GWP), see Table 4. The unit of the category indicator result is kg CO_2-equivalents/kg gas.

Table 4: Terminology for the example of the impact category climate change (based on ISO 14044:2006, p.37)

Impact category	Climate change
Characterization model	Baseline model of 100 years of the International Panel of Climate Change (IPCC 2007)
Category indicator	Infrared radiative forcing
Characterization factor	Global Warming Potential (GWP) for each greenhouse gas
Unit of category indicator result	kg CO_2-equivalents/kg gas

Multiplying the LCI results by the characterization factors gives the category indicator result for each substance. For example, if the LCI results include 1 kg of carbon dioxide (CO_2), 0.1 kg of Tetrafluoromethane (CF_4), 10 kg of methane (CH_4), and 1 kg of dinitrogen monoxide (N_2O), the aggregated results for the impact category climate change equals a GWP of 1099 kg CO_2-equivalent (see Figure 9).

[12] CML-IA characterization factors provided by the Institute of Environmental Sciences of University Leiden can be downloaded at https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed March 1st 2016)

In this way, all outputs of the LCI are aggregated into indicators. Some substances in the LCI are classified into more than one impact category, e.g. nitrous oxides (NO_X) contribute to the impact category *acidification* with a characterization factor of 0.7 kg SO_2-equivalent/kg gas, but also to *eutrophication* with a characterization factor of 0.13 kg PO_4^{3-}-equivalent/kg gas (see Figure 9).

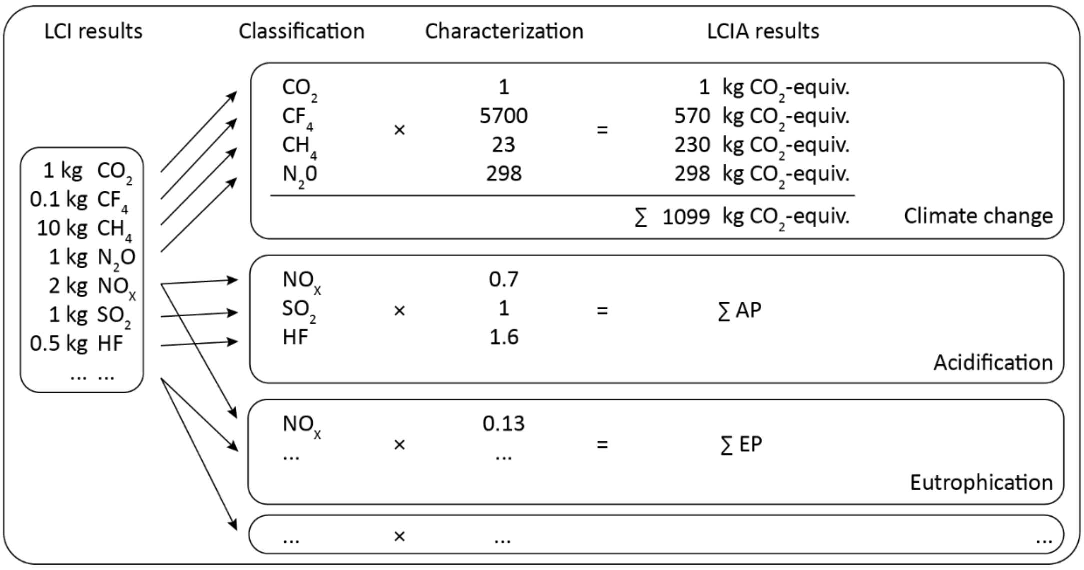

Figure 9: Example of LCIA (data based on Klöpffer & Grahl 2009, pp.318-321)

Optionally, the category indicator results can be normalized, grouped, and weighted. Normalization might provide a clearer indication of the significance of particular indicator results (Crawford 2011, p.57). The indicator results are divided by a selected reference value, for example, the results for GWP are divided by the total annual GWP of Germany. The aim is to reveal which indicator contributes more to the overall problem area (König et al. 2009, p.47).

Grouping sorts the impact categories by their particular characteristics or by ranking their significance. While sorting should not include value-choices, ranking introduces a hierarchy, and is therefore based on value-choices (Klöpffer & Grahl 2014, p.199).

Weighting relates the different indicators by multiplying them with numerical factors and aggregating them across impact categories. The aggregation into one single indicator might facilitate the communication of results to non-LCA-experts. It must be kept in mind that weighting steps are based on value-choices and are not scientifically based (ISO 14040:2009, p.18). The judgment as to which indicator is more important than another depends on individual goals, and differs greatly between different countries or organizations.

The impact categories noted previously, for example climate change, are so-called *midpoint* impact categories. These represent a problem-oriented approach because they relate to the environmental problem fields shown in Table 3. Damage-oriented approaches use so-called *endpoint* impact categories to translate environmental impacts into issues of concern, such as human health, the natural environment, and natural resources. *ReCiPe* (Goedkoop et al. 2013, p.2) uses both 18 midpoint and 3 endpoint categories (see Figure 10). The endpoint categories aim to be easier understood by decision makers, but they have a higher level of uncertainty (Goedkoop et al. 2013, p.2). The three endpoint categories can be further aggregated into a single score. Other methods to provide single-score results are *Eco-Indicator 99* (Goedkoop & Spriensma 2001, pp.12-19) or the Swiss *Method of Ecological Scarcity* (UVEK & BAFU 2008, pp.1-3). The latter employs *eco factors* to relate between the actual emission situation in Switzerland and political targets (Frischknecht & Büsser Knöpfel 2013, p.41). The resulting single indicator is called *eco points* (*Umweltbelastungspunkte* - UBP). As the actual emission situation changes constantly, the eco factors have to be updated regularly. The method depends on the regional situation and has to be adapted to a national or regional context before using it in other European countries. A study describing the adaption for Germany can be found in Ahbe et al. (2014, pp.11-26).

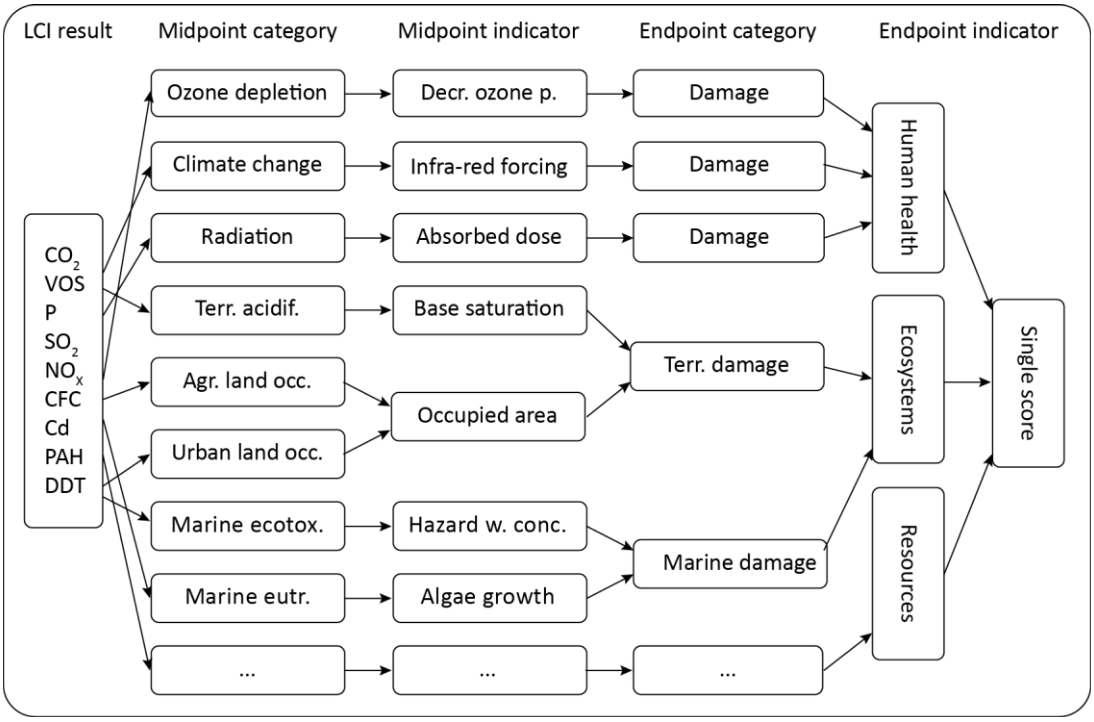

Figure 10: Example of endpoint indicators based on ReCiPe, based on Goedkoop et al. (2013, p. 3)

1.2.1.4. Life cycle interpretation

In the fourth stage, the quantitative results of stages 2 and 3 are interpreted qualitatively in order to identify significant issues. According to ISO 14044:2006, an evaluation that considers completeness, sensitivity, and consistency checks should be added. Finally, conclusions and recommendations for decision-makers should be formulated and limitations made clear.

1.2.1.5. Limitations of LCA

The main characteristic of LCA is its holistic approach, which is both its major strength and limitation (Guinée et al. 2001, p.6). The limitations of the LCA method have to be clear for its application. Detailed discussions about the limitations of LCA can be found in the literature, for example in Krozer & Vis (1998, pp.53-56), Ayres (1995, pp.202-211), Heijungs & Huijbregts (2004, pp.2-5), or Finnveden (2000, pp.230-233). Here, the main limitations are presented in six points:

1. **Potentials instead of absolute values**: It is crucial to keep in mind that LCA results are not able to predict precise or absolute environmental impacts (El Khouli et al. 2014, p.23). The results of an LCA study can only indicate the potential environmental impact caused by a product or service. The environmental impacts of a single product throughout its life cycle cannot be studied empirically. Furthermore, environmental impacts that are observed in the world cannot be connected to products by an experimental method. LCA practitioners have to rely on models that are only valid within a certain context (Klöpffer & Grahl 2014, p.181).
2. **Place independence**: The characterization causes the results to be independent of time and place (ISO 14040:2009, p.31). Therefore, LCA is not able to quantify impacts and risks on the environment at a specific location. König et al. (2009, p.38) propose to employ *risk assessment* for this purpose.
3. **Time independence**: Typically, LCA models are linear steady-state models of physical flows (Guinée et al. 2001, p.6). The models lack temporal dimensions, making it impossible to specify the point in time that an emission occurs. Recent developments on *dynamic LCA* include scenarios for changing boundary conditions and assumptions, e.g. the electricity mix of a country, see Pehnt (2006, pp.62-67), Collinge et al. (2013, pp.540-544). Dynamic LCA requires additional assumptions and introduces further complexity, and is therefore not part of this thesis.
4. **Limitations of impact categories**: The impact categories cover a wide range of environmental aspects, but do not cover all relevant environmental aspects (Finnveden 2000, p.231). Klöpffer and Grahl state: "A list of environmental problem fields is always incomplete because it can only correspond to the current level of knowledge and the public reception of environmental problems" (Klöpffer and Grahl 2014, p.202).

5. **Assumptions**: „Although LCA aims to be science-based, it involves a number of technical assumptions and value choices.“ (Guinée et al. 2001, p.14). These assumptions can have a great influence on the results, making regulation and standardisation necessary. The ISO standards provide a general framework, and EN 15978:2012 provides the regulations for buildings. Nevertheless, the regulations leave room for assumptions, e.g. in the allocation process (El Khouli et al. 2014, p.23). To guarantee objectivity, the assumptions have to be made as transparent as possible (Guinée et al. 2001, p.6).
6. **Uncertainties:** LCA involves numerous uncertainties. The problem is discussed in the literature from different perspectives, e.g. (Huijbregts 1998, pp.273-277), Björklund (2002, pp.64-65), Ciroth (2006, pp.5-11). Huijbregts (1998, p.273) distinguishes between three types of uncertainties: parameter uncertainties, model uncertainties, and normative uncertainties. Parameter uncertainties include uncertainties in the input data and characterization factors. Normative uncertainties due to choices are inevitable. These include the allocation method and the time horizon amongst others. Model uncertainties mainly result from the characterization of LCI data. According to Klöpffer & Grahl (2014, p.190), there are no generally accepted methodologies for consistently and accurately associating inventory data with specific potential environmental impacts. An overview of ways to treat uncertainty in LCA studies is provided by Heijungs & Huijbregts (2004, pp.3-6).

1.2.2. LCA for buildings

To provide a European framework for evaluating the sustainability of buildings, the technical committee CEN/TC 350 developed the standard EN 15643:2010. It consists of four parts: one part describing the general framework and three parts each referring to one aspect of sustainability, namely environmental, economic, and social performance (see Figure 11). The framework for the assessment of environmental performance EN 15643-2:2011 refers to two main standards for building-related LCA: EN 15978:2012 for buildings and EN 15804:2012 for building products. These standards provide guidance on how to apply LCA to buildings and define system boundaries, product category rules (PCRs), allocation methods, etc. EN 15804:2012 defines the PCRs for *Environmental Product Declarations* (EPDs), which aim to communicate “verifiable, accurate, non-misleading environmental information for products and their applications” (EN 15804:2012, p.7). An EPD is held by the manufacturer of the product and is a voluntary disclosure of the environmental impact of a product, but it does not mean that the product meets an environmental performance standard. In addition to these standards, the *ILCD Handbook*[13] gives detailed information on the application of LCA. The *EebGuide*[14] (Wittstock et al. 2012) tries to combine provisions and guidance from the European standards and the ILCD Handbook.

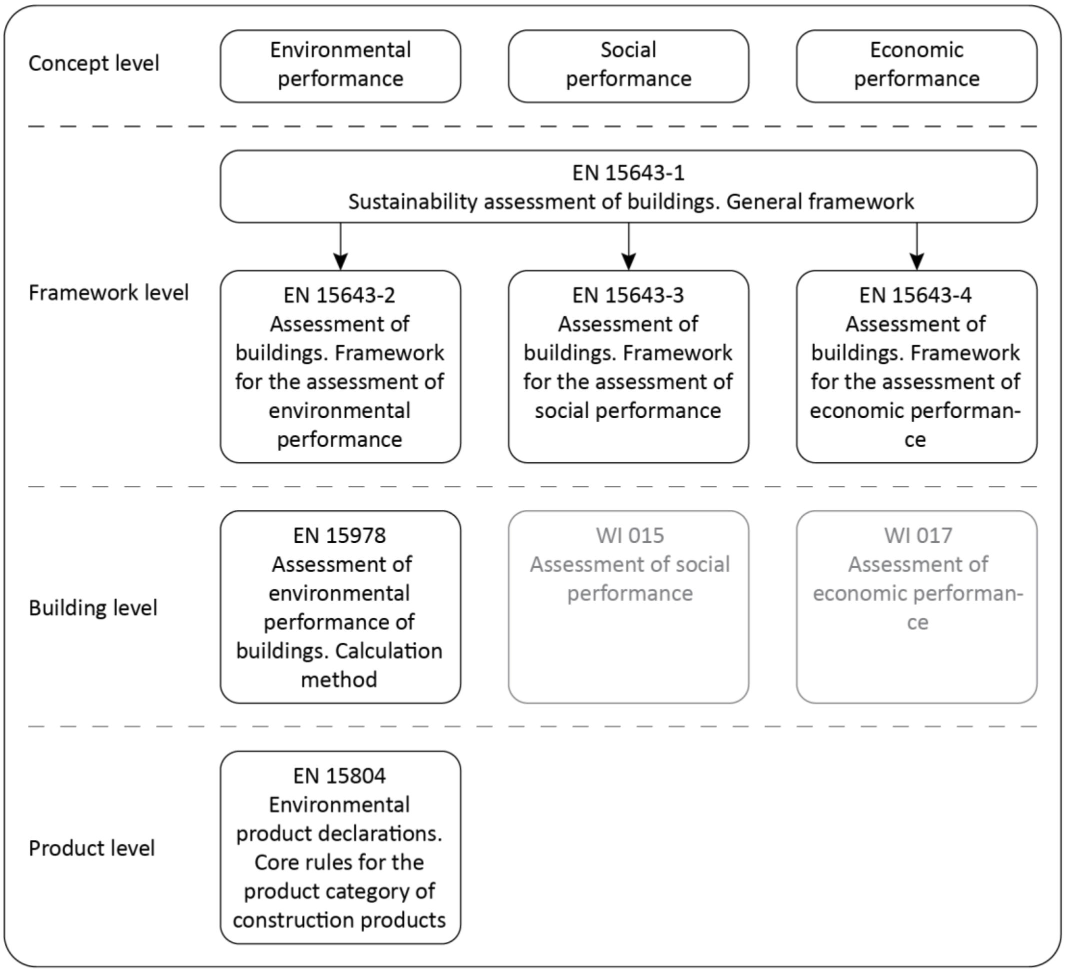

Figure 11: Work programme of CEN/TC 350 (based on EN 15643-1:2010 p.6)

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[13] The ILCD handbook was developed by the Institute for Environment and Sustainability at the European Commission Joint Research Centre. It consists of a set of documents for guidance that are in line with the international standards on LCA and can be accessed online: http://eplca.jrc.ec.europa.eu/?page_id=86 (accessed March 2nd 2016)

[14] The EeBGuide is an operational guideline for LCA of buildings and can be accessed online: http://www.eebguide.eu/?page_id=704 (accessed March 2nd 2016)

1.2.2.1. Functional unit and system boundaries

According to EN 15978:2012 (p.16), the functional equivalent of a building or a building component must contain information about aspects such as the type of building, type of use, technical or functional requirement, and requested service life. The functional equivalent can also refer to a unit, for example the DGNB uses 1 m² of net floor area and 1 year of operation as reference unit. In this case a reference study period (RSP) must be selected. For building certification in Germany, 50 years is the standard period, while in Switzerland 60 years is used (cf. SIA 2032:2012, p.22). Depending on the task, for example for refurbishment of an existing building, it might be more realistic to apply an RSP of 30 years for the rest of the building's life; in other case studies, 100 years could be applied. Functional units can also relate to the intended use, such as the number of user hours for an office building. To foster floor space efficiency, the relation to the user within the functional equivalent is useful (Hollberg & Klüber 2014, p.63). Relating solely to net floor area might favour large buildings (Mithraratne et al. 2007, p.32) and decrease space efficiency.

For the LCA of buildings, two kinds of system boundaries have to be defined. In addition to the system boundaries on the product/material level—the border between the technosphere and the natural environment — described in 1.2.1.1, the system boundaries at the building level need to be determined. Therefore, both European standards for LCA of buildings, EN 15804:2012 and EN 15978:2012, divide the life cycle of buildings and building products into five stages: Product (A1-A3), Construction (A4-A5), Use (B), End-of-life (C), and an additional stage for benefits beyond the system boundaries (D) (see Figure 12).

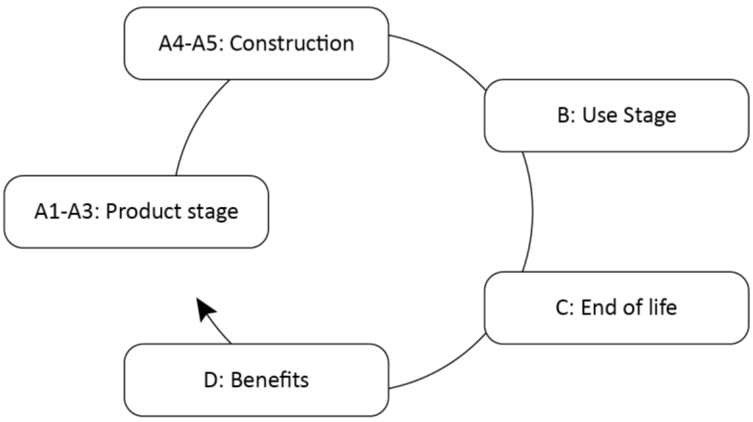

Figure 12: Life cycle of a building according to EN 15978:2012

These stages are divided into life cycle modules (see Table 5). First of all, the product stage (A1-A3) describes the production of materials until the gate of the manufacturer, which is therefore also called *cradle-to-gate* analysis. According to EN 15804:2012 (p.12), these three modules are mandatory for all EPDs, and the results can be aggregated for the whole product stage (A1-A3) (EN 15804:2012, p.16). In general, data for these modules can be easily provided by the manufacturer with a high degree of certainty, since they are usually aware of the raw materials, the means of transportation for the material to the manufacturing plant, and the energy needed for production.

The transportation module (A4) depends on the distance between the construction site and the manufacturer's plant. Kellenberger & Althaus (2009, pp.823-825) show that this transportation can become relevant in some cases. The influence of the transportation in their studies of typical building envelopes ranges between 5% and 8% for the aggregated EcoIndicator 99 (H/A). The Swiss standard for embodied energy in buildings mentions ranges between 2 and 8% for embodied primary energy (SIA 2032:2010, p.14). However, in early design stages, the location of the factory is usually not known.

Module A5 describes the construction process. For some materials, specific data - such as the pouring of concrete with pumps - can be found in the literature or in EPDs, but in general data for this module are rare. According to Kellenberger & Althaus (2009, p.825), the influence of the building process, exclusive transport of equipment and construction crew, and temporary heating, is less than 8% of the total EcoIndicator 99 (H/A).

Module B describes the use phase of the building, including use (B1), maintenance (B2), repair (B3), replacement of building components (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7). Module B1 includes emissions resulting from the expected use of the building components, e.g. emission of substances from façades. Maintenance (B2) is defined as the combination of all planned actions during the service life to maintain the building in a state in which it can deliver its required functional and technical performance (Wittstock et al. 2012, p.232), e.g. repainting or inspection of building service components. Energy and water needed for cleaning as part of maintenance are accounted for in this module. Repair (B3) refers only to corrective, responsive, or reactive actions in response to the loss of performance of a building component or building part. Module B3 can include partial replacement, e.g. the replacement of a broken window pane. However, the complete replacement of building components, if their reference service life is lower than the reference study period, is accounted for in module B4. Refurbishment (B5) covers measures to increase the performance of a building, such as a major change to the internal layout or a new heating system. Module B6 includes all energy used by technical systems within the building to operate the building, e.g. heating, cooling, and ventilation. Energy use within the building not directly linked to operating the building, such as computers or refrigerators, has to be declared separately. Module B7 includes all use of water and its treatment related to the operation of the building. Water use for systems not directly linked to operating the building, such as a dishwasher, has to be declared separately.

At the EOL stage of the building, similar difficulties as for the construction process arise. Details of the demolition (C1) and the transportation to waste processing plants (C2) are usually unknown. Environmental data based on typical scenarios are available for most materials for the waste processing (C3) and disposal (C4). It must be kept in mind that the assessment is based on current scenarios and technology. The processes for the EOL of the building which lies 50 to 100 years in the future might be very different.

Module D describes benefits beyond the system boundaries, such as a benefit for incineration of waste which can be used for energy production. The assessment of Module D introduces a variety of difficulties (Wastiels et al. 2014, p.3). As noted earlier, after defining the system boundaries, the time aspect is lost in the data aggregation for LCA. This can become problematic, as buildings usually have a very long lifetime. The emissions saved through the incineration of waste and use of the resulting energy instead of burning fossil fuels is accounted for with the current energy mix. However, the EOL might lie 100 years in the future, with a different energy mix or different waste scenario. Benefits at the beginning of the life cycle, such as carbon sequestration of natural resources, should therefore ideally be calculated differently than benefits at the EOL.

Table 5: Life cycle modules (based on EN 15978:2012, p.21)

Product			Construction		Use Stage							End of Life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Re-use, recovery and recycling potential

1.2.2.2. Operational energy demand calculation

In order to be able to calculate the life cycle module B6, the operational energy demand of the building must be known. The use phase of buildings can range from 30, to 50, to over 100 years, making the operational energy demand calculation an important parameter for the LCA of buildings.

In general, energy demand in buildings can refer to three types of definitions (cf. DIN V 18599-1:2011, p.11):

- **Primary energy**: energy as it is available in the natural environment, i.e. the primary source of energy.

- **Final energy**: energy which the consumer receives at the boundary of the building envelope.
- **Useful energy**: energy which is an input to an end-use application, i.e. the energy provided in a room in the form of heat.

To calculate the final energy demand, the useful energy demand can be multiplied by a factor for losses within the building. The primary energy demand can be calculated by multiplying the final energy demand with a primary energy factor dependent on the energy carrier, such as gas or electricity.

Different types of energy demand occur during the use phase. Lützkendorf et al. (2015, p.65) distinguish between two types: *building-related operations* and *user-related operations* (see Table 6). While the architect has no influence on user-related operations, energy demands for building-related operations, such as space heating and cooling, are directly influenced by the architect's design. The thermal quality of the building envelope and the choice of heating system, but also geometric parameters, such as the window layout, amongst others, determine this kind of energy demand. However, it should be noted that the user's behaviour also influences energy consumption to a certain degree, e.g. through the temperature that tenants set in their rooms (Hegger et al. 2007, p.189).

Table 6: Examples for building- and user-related operations based on Lützkendorf et al. (2015, p.67)

Building-related operations	User-related operations
Space heating	Plug-in supplementary lighting
Space cooling	Household / Office appliances
Air movement	Refrigerator
Fixed lighting	Hot water
Auxiliary energy (e.g. for heat pumps)	Devices in data centre
Indoor transportation	Other specific functional devices

In general, there are two possibilities for determining the building's operational energy demand: *dynamic building performance simulation* (DBPS), such as *EnergyPlus*[15] or

[15] EnergyPlus is an open source whole-building simulation software. The development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), and managed by the National Renewable Energy Laboratory (NREL). The software is available at https://energyplus.net/downloads (accessed February, 9th 2016)

TRNSYS[16], and *quasi-steady state methods* (QSSM), such as ISO 13790:2008, DIN V 18599-2:2011, or DIN V 4108-6:2003.

For both methods it is necessary to define a boundary for the energy balance, which corresponds to the thermal envelope of the building. To calculate the heating demand, heat sinks and useable heat sources are balanced within this defined boundary and a defined time step. To calculate the cooling demand, excess heat sources are balanced. The resulting heating or cooling demand has to be provided through building services.

The main difference is the time steps in which the energy balance is established. Time steps for DBPS usually range between 1 minute and 1 hour. DBPS considers the thermal heat storage capacity in every time step. Thus, the heating and cooling behaviour can be simulated in detail. Furthermore, DBPS allows for detailed simulation of dynamic regulation, such as dynamic shading elements that track the sun's movement. As such, DBPS is advisable for complex situations, because it allows for detailed modelling of complex systems and their interrelation. However, DBPS requires a great number of boundary conditions, and input of these boundary conditions requires extensive knowledge on the part of the user. In EnergyPlus, for example, the user can choose between different heat balance and surface convection algorithms, which have a significant impact on the results. This makes it difficult to apply for architects without a profound education in building physics. Furthermore, the simulation takes a lot of computational time. Depending on the size of the building, the simulation can take between 20 seconds and 5 minutes on a standard PC[17].

QSSM usually balance energy sources and sinks on a monthly basis, and consider the heat stored in the building material only via a global factor. Due to the simplification, some aspects are not considered, and complex interactions cannot be represented. The simplified approach allows for quick feedback of results, with computation times ranging from 0.1 to 5 seconds, making QSSM much more time-efficient for the optimization of simple systems, such as residential buildings. According to van Dijk et al. (2006, p.262), the accuracy of the results from QSSM are acceptable for residential buildings in warm, moderate, and cold climates. QSSM is also used for national energy saving regulations, such as EnEV 2014

[16] TRNSYS is a graphically based software environment used to simulate the behaviour of transient systems. It includes TRNSYS3D - a plugin for SketchUp that allows the user to draw multi-zone buildings and import the geometry. The software is available at http://www.trnsys.com/ (accessed March 2nd 2016)

[17] Here, standard PC refers to an Intel i3 processor 2.1 GHz and 8GB RAM.

(Bundesregierung 2013), and European energy performance certificates (Economidou et al. 2011, p.64).

An overview of the main characteristics of both methods is provided in Table 7.

Table 7: Characteristics of quasi-steady state methods and dynamic building performance simulation

	QSSM	DBPS
Time step	1 month	1 minute to 1 hour
Calculation method for heat conduction	Analytical function for steady-state heat conduction	Analytical functions or differential equations for dynamic heat conduction
Relation between building surfaces	No interaction between surfaces	Interaction between surfaces is considered
Consideration of solar radiation	Dependent on cardinal direction (azimuth)	Dependent on cardinal direction (azimuth) and altitude
Consideration of heat storage capacity	Global factor	Direct consideration in every time step
Consideration of building services	Global factor for efficiency	Detailed simulation of heating and cooling phases
Consideration of moisture	No	Optionally
Computation time	Low (0.1 to 5 seconds)	High (20 seconds to 5 minutes)
Accuracy	Low to moderate	High

The building-related operations defined by Lützkendorf et al. (2015, p.65) are further divided into energy demand affected by the design and energy demand not affected by the design.

Energy demand significantly affected by the building design, such as heating demand, is most important for architects, because they have a great influence on this kind of energy demand. The thermal quality of the building envelope, the window layout, and the choice of heating system, among other variables, directly influence this kind of energy demand. Therefore, it is calculated using QSSM or DBPS. It should be mentioned that the user's behaviour also influences energy consumption to a certain degree, e.g. through the temperature that tenants set in their rooms (Hegger et al. 2007, p.189).

The architects' influence on other kinds of energy demand, such as electricity for lighting or escalators, is limited. Nevertheless, it can be useful to assess this design-independent energy demand to provide a relation for the optimization potential of the design-affected kind in the context of the whole building. Therefore, this kind of energy demand is integrated optionally using statistical values.

The first German heat insulation ordinance (*Wärmeschutzverordnung*) was published in 1977. Since then, further regulations have been passed and are continuously refined and updated in all European countries. Most European countries now have implemented national regulations for building energy performance which comply with the demands of the European Directive on the Energy Performance of Buildings (EU 2010). In Germany, the current energy saving ordinance, *EnEV 2014* (Bundesregierung 2013), stipulates a monthly energy balance using QSSM. The algorithms for calculating the energy demand are defined in DIN V 18599-2:2011. At present, the older DIN V 4108-6:2003 can still be used for residential buildings.

As noted in the introduction, since the 1980s much attention has been paid to the operational energy demand and - compared to LCA - the field is well known. For the objective of this thesis, there is no need for further research, and existing approaches are integrated into the new LCA method developed for this thesis.

1.2.2.3. Category indicators used for buildings

Most LCA studies for buildings use predefined data such as EPDs. This means that the LCI and LCIA as defined in ISO 14040:2009 merge into one stage (Lasvaux & Gantner 2013, p.410) (see Figure 13). As a result, the classification and characterization as described in 1.2.1.3 have already been carried out, and the complexity of the LCI and LCIA are reduced to multiplying the mass of the building material by the environmental data from EPDs or databases.

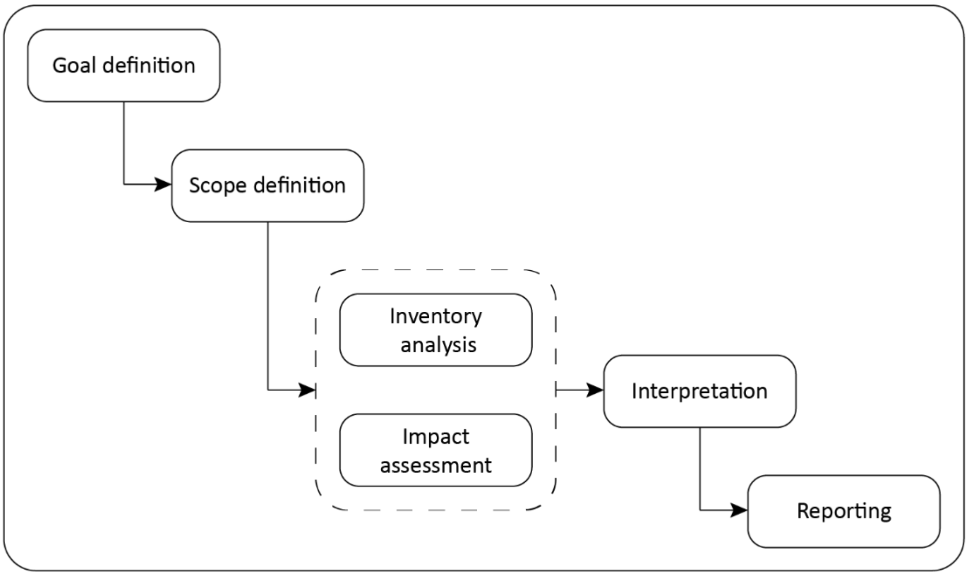

Figure 13: Representation of the different steps of the LCA framework (Lasvaux & Gantner 2013, p.409)

The environmental data can include different impact category indicators. EN 15804:2012 divides those into 'parameters to describe environmental impacts' (output-related indicators) and ‘parameters to describe the resource demand’ (input-related indicators). Output-related indicators are shown in Table 8. These indicators should be applied to the LCA of buildings according to EN 15978:2012.

Table 8: Output-related parameters (EN 15804:2012, p.33)

Impact category	Parameter	Abbreviation	Unit
Climate Change	Global Warming Potential	GWP	kg CO_2-equiv.
Ozone Depletion	Ozone Depletion Potential	ODP	kg R11-equiv.
Acidification of soil and water	Acidification Potential	AP	kg SO_2-equiv.
Eutrophication	Eutrophication Potential	EP	kg PO_4^{3-}-equiv.
Formation of Photo Oxidants	Photochemical Ozone Creation Potential	POCP	kg CH_4-equiv.
Abiotic Resource Depletion*	Abiotic Resource Depletion Potential element	ADPe	kg Sb-equiv.
Abiotic Resource Depletion*	Abiotic Resource Depletion Potential fossil	ADPf	MJ

*This indicator is currently under study and its application might be revised in the next version of EN 15804

Various characterization models for output-related indicators exist. EN 15804:2012 (p. 31) recommends using the characterization factors provided by the *European Reference Life Cycle Database* (ELCD)[18]. The characterization factors for ADP should be taken from CML[19]. The standard employs midpoint indicators only, and does not employ any aggregation into a single point indicator. As such, it follows the recommendations of ISO 14040:2009. The individual impact categories are described in Appendix A.

Input-related parameters are shown in Table 9.

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[18] The database can be accessed on the website of the Joint Research Centre of the European Commission http://eplca.jrc.ec.europa.eu/ELCD3/index.xhtml (accessed March 2nd, 2016)

[19] CML-IA characterization factors provided by the Institute of Environmental Sciences of University Leiden can be downloaded at https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed March 1st 2016)

Table 9: Input-related parameters (EN 15804:2012, p.34)

Parameter	Unit
Use of renewable primary energy, excluding renewable primary energy resources used as raw materials	MJ, lower heating value
Use of renewable primary energy resources used as raw materials	MJ, lower heating value
Total use of renewable primary energy resources (PERT)	MJ, lower heating value
Use of non-renewable primary energy, excluding non-renewable primary energy resources used as raw materials	MJ, lower heating value
Use of non-renewable primary energy resources used as raw materials	MJ, lower heating value
Total use of non-renewable primary energy resources (PENRT)	MJ, lower heating value
Use of secondary material	kg
Use of renewable secondary fuels	MJ, lower heating value
Use of non-renewable secondary fuels	MJ, lower heating value
Total use of net fresh water	m^3

While EN 15804:2012 and EN 15978:2012 list all of these parameters, most LCA studies and building certification systems only employ the use of primary energy as an indicator for the evaluation of the building. The primary energy demand (Primary Energy Total, PET) is divided into renewable (Primary Energy Renewable Total, PERT) and non-renewable parts (Primary Energy Non-Renewable Total, PENRT). The primary energy demand, also called *Cumulative Energy Demand* (CED), is strictly speaking not an indicator, as it does not correspond to any impact category (Klöpffer & Grahl 2014, p.220). Nevertheless, it is a very useful characteristic, which can be determined with a small uncertainty (Finnveden & Lindfors 1998, p.65).

In addition to the primary energy demand, the use of water and land can also be employed as input categories. The use of fresh water is a controversial indicator (cf. Kounina et al. 2013, pp.708-709). Fresh water is a renewable resource with a complex global water cycle, but scarcity of water is a significant problem in many regions of the world (Berger & Finkbeiner 2010, p.920). Land use is an important indicator with respect to its potential as a greenhouse gas sink, such as for CO_2 and N_2O (Klöpffer & Grahl 2014, p.227). According to König et al. (2009, p.44), there is no consistent method to incorporate the impact of land use in LCA. An overview of different concepts to assess water and land use is given in Klöpffer & Grahl (2014, pp.227-233).

Further categories describe the production of waste in terms of the type of hazard that it poses (see Table 10), as well as material and energy outflows with potential further utility, such as recyclable material or exported energy (see Table 11).

Table 10: Indicators describing waste (EN 15804:2012, p.34)

Indicator	Unit
Hazardous waste disposed	kg
Non-hazardous waste disposed	kg
Radioactive waste disposed	kg

Table 11: Indicators describing material and energy outflows from the system (EN 15804:2012, p.35)

Indicator	Unit
Components for reuse	kg
Materials for recycling	kg
Materials for energy recovery	kg
Exported energy	MJ

1.2.2.4. Data sources

Many different types of data are required for the LCA of a building. The characteristics and data sources are described in the following. This data can be broadly categorized as being required either for the embodied or the operational impact calculation (see Table 12).

Table 12: Categories of data needed for LCA for buildings

Embodied impact	Operational impact
Environmental data for building materials and services	Environmental data for energy carriers
Data on the reference service lives (RSL) of building materials	Data for energy demand calculation a) Physical properties b) Climate data c) User data

Environmental data for building materials and services

Conventional LCA for products or services is usually carried out using predefined LCI data. This LCI data can be found in databanks such as *ELCD*, *US LCI*[20], *Ecoinvent*[21], or the *GaBi*

[20] US LCI is a free life cycle inventory database provided by the U.S. National Renewable Energy Laboratory accessible at https://www.lcacommons.gov/nrel/search (accessed March 2nd 2016)

database[22]. Further databanks can be found on the website of EeBGuide[23]. These databanks include some LCI data for building materials, but generic LCA Software, such as *GaBi*[24], *Sima Pro*[25], or *OpenLCA*[26], have to be employed to carry out the LCIA.

As noted earlier, predefined LCIA datasets are typically employed in the LCA of buildings. For building materials, these datasets are categorized as either specific, average, or generic (Silvestre et al. 2015, p.732):

- Specific data is collected at the manufacturer's plant for one specific product and usually provided to the public in the form of an EPD. Passer et al. (2015, p.1212) provide a detailed overview of different sources for building material EPDs.
- An average dataset combines various specific datasets. It might be useful to have national averages for certain product groups, for example.
- Generic data is used to model processes that are not under the manufacturer's control, for example transportation of raw material on ships. Additionally, generic data on building materials is used as a surrogate if no specific data are available (EN 15978:2012, p.41).

In general, it is difficult to combine data from different databanks. Silvestre et al. (2015, pp.741-746) analyse various European datasets, including EPDs and generic data for stone wool insulation boards. While all datasets have similar boundaries (A1-A3), they are based on different PCRs, cut-off, and allocation rules. Additionally, datasets for different years show differences in the background data of the electricity mix. In general, an EPD is valid for

[21] Ecoinvent is provided by the Swiss Ecoinvent centre, see http://www.ecoinvent.org/database/database.html (accessed March 2nd 2016)

[22] GaBi database is a commercial database provided by thinkstep, see http://www.gabi-software.com/databases/gabi-databases/ (accessed March 2nd 2016)

[23] The EeBGuide website is provided by the Fraunhofer Institute for Building Physics http://www.eebguide.eu/?page_id=669 (accessed March 2nd 2016)

[24] GaBi is an LCA software developed by thinkstep, see http://www.gabi-software.com/international/index/ (accessed March 2nd 2016)

[25] SimaPro is developed by PRé and can be obtained at https://www.pre-sustainability.com/simapro (accessed March 2nd 2016)

[26] OpenLCA is an open source LCA software and can be downloaded at http://www.openlca.org/downloads (accessed March 2nd 2016)

five years (EN 15804:2012, p.44), but a lot of datasets are out of date, and have not yet been replaced with current data. EPDs can be found on different national platforms, such as the *Institut Bauen und Umwelt*[27] or *INIES*[28], and international online platforms, such as *envi-rondec*[29]. Further sources for EPDs related to buildings can be found on the website of EeBGuide.

The ILCD Handbook (JRC European commission 2011, p.184) recommends using specific data in the form of EPDs. In early design stages, the exact product manufacturer is usually unknown, making it more realistic to use generic or average data. Lasvaux et al. (2015, p.1482) show the differences in results from the application of different EPDs and generic data. They conclude that mixing EPDs calculated with different background data may not be appropriate. Silvestre et al. (2015, p.734) propose a method to establish generic data from different specific datasets. This could help to define national datasets which would provide a common ground, for example for the application in building certification systems. At present, the assumptions and data behind the LCAs of individual buildings vary greatly, making a comparison of different buildings and an external verification difficult (Wittstock et al. 2012, p.12).

There are various national platforms for building material LCIA data. Table 13 lists the platforms with generic data that are the most practical at present. The EeBGuide website lists further databases, but those are out of date, or only include a very limited number of datasets and are therefore impractical for application.

[27] The EPDs provided by Institut Bauen und Umwelt (IBU) can be accesses at http://construction-environment.com/hp421/EPD.htm?ITServ=C3bde5731X153378579e3X67ba (accessed March 2nd 2016)

[28] INIES database can be accessed at http://www.inies.fr/life-cycle-inventories/ (accessed March 2nd 2016)

[29] This international database is provided by EPD International AB and can be accessed at http://environdec.com/EPD-Search/ (accessed March 2nd 2016)

Table 13: Generic LCIA data sources for building materials

Name	Type of data	Country	Publisher	Website
Ökobau.dat	specific, average, generic	Germany	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety	http://www.oekobaudat.de/en.html
KBOB "Ökobilanzdaten im Baubereich"	generic	Switzerland	Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (KBOB)	http://www.eco-bau.ch/
Baubook	specific, average, generic	Austria	Baubook GmbH	https://www.baubook.info/
The Athena Institute database *	average, generic	Canada	Athena Institute	http://www.athenasmi.org/our-software-data/lca-databases/
Leitfaden	average, generic	Luxembourg	Centre de Ressources des Technologies pour l'Environnement (CRTE)	http://www.crtib.lu/Leitfaden/content/DE/116/

* Only applicable in combination with Athena Impact Estimator software

Reference service life data

The lifetime of a building material depends on a number of influences, such as weather conditions, construction quality, or maintenance (Bahr & Lennerts 2010, p.24). In some cases, the economic situation determines whether a building is still in use, refurbished, or demolished, although it might not be necessary due to functional or technical deficiencies. Thus, it is important to distinguish between the economic and the technical service life. The economic lifetime is very hard to predict and not considered here. The reference service life (RSL), as referred to in the context of LCA, always describes the technical service life.

Data for building material RSL is important for LCA, because it determines the number of replacements of a material within the reference study period (RSP). As noted previously, the RSL depends on a great number of influencing parameters. In the literature, various studies to determine building material RSLs can be found, e.g. Hirschberger et al. (1994), Kalusche (2004), Pfeiffer & Arlt (2005). ISO 15686-8:2008 proposes a method to increase or decrease default RSL values by multiplying them with factors. Bahr & Lennerts (2010, pp.57-83) developed this method further in order to allow for the application in practice. Applying this factor method and using data from the literature, Ritter (2011, p.119) established 33 determining factors in seven categories for most typical building materials. By means of Monte Carlo simulation, he developed a list of data, including average RSL, minimum RSL, and maximum RSL. His research shows great depth, and it can be assumed that it is the most realistic data currently available.

Currently, for LCA in German building certification systems, a list of RSLs provided by BBSR[30] (German Federal Institute for Research on Building, Urban Affairs and Spatial Development) is used, although some RSLs seem to be too high when compared to Ritter (2011, pp.225-234).

Environmental data for energy carriers

The operational impact is calculated by multiplying the operational energy demand by environmental data for the energy carriers employed. Similar to the environmental data for building materials explained previously, this data can be found in various databanks (see Table 14).

Table 14: Data sources for energy carriers

Name	Country	Publisher	Website
Ökobau.dat	Germany	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety	http://www.oekobaudat.de/en.html
Probas	Europe	Umweltbundesamt	http://www.probas.umweltbundesamt.de/php/index.php
Gemis	Europe	Internationale Institut für Nachhaltigkeitsanalysen und -strategien	http://www.iinas.org/gemis-download-de.html, also integrated in Probas
US LCI database	United States of America	National Renewable Energy Laboratory	https://www.lcacommons.gov/nrel/search

Physical properties

First of all, the physical properties have to include the material density needed to convert between volume and mass. For energy demand calculation, the thermal conductivity is necessary in order to determine heat loss (or entry) because of transmission through the

[30] The table with RSL data used for BNB certification system is called *Nutzungsdauern von Bauteilen zur Lebenszyklusanalyse nach BNB* and is provided by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (Bundesinstitut für Bau-, Stadt- und Raumforschung - BBSR). It can be downloaded at http://www.nachhaltigesbauen.de/baustoff-und-gebaeudedaten/nutzungsdauern-von-bauteilen.html (accessed March 12th 2016)

building envelope. When employing DBPS, the specific heat capacity and factors for thermal, solar, and visual absorptance are also necessary.

The physical properties of building materials can be found in different sources. If the specific material is known, the most accurate data can be found in EPDs or directly in the technical specifications provided by the manufacturer. If the specific manufacturer is unknown, generic data has to be employed. The international standard EN ISO 10456:2010 provides tables with the density, conductivity, specific heat capacity, and vapour resistance for most common building materials. The German standard DIN 4108-4:2013, which is based on EN ISO 10456:2010, provides even more detailed information on the thermal conductivity in dependence on the density of the material.

The density is the link between environmental data for materials provided in *ökobau.dat*[31] and the data needed for energy demand calculation. One issue when combining datasets is matching the right density of the material. The datasets of ökobau.dat sometimes list densities not as exact values, but as ranges. For example, a range from 155 to 250 kg/m³ is provided for wood fibre insulation boards (WFIB). As the calculation of the environmental impact is mass-based, the result is highly dependent on the density. In the example of wood fibre insulation boards (WFIB), when assuming 250 kg/m³ instead of 155 kg/m³, the result is over 60% higher. The density also influences the thermal conductivity to a great extent. As noted previously, DIN 4108-4:2013 provides the thermal conductivity for various densities.

Climate data

The type of climate data required depends on the method of energy demand calculation. For DBPS, a detailed weather file is needed, which is based on typical weather data (TWD). TWD consists of hourly values of solar radiation and meteorological elements for a one year period (Gazela & Mathioulakis 2001, p.339). It is based on measurements over many years and specially selected so that it presents the full range of weather phenomena, while still giving annual averages that are consistent with the long-term averages for the specific location. For QSSM based on DIN V 18599-2:2011, only monthly average temperatures and solar radiation data are required. For Germany, these are provided in DIN V 18599-10:2011, which divides Germany into 15 different climatic regions.

[31] The online database ökobau.dat contains more than 700 different building products and complies with EN 15804:2012. It is provided by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety and can be accessed at http://oekobaudat.de/ (accessed March 12th 2016)

User data

User data includes heating and cooling set points, operating hours, and internal loads, among other data. Typical user profiles for different kinds of buildings can be found in standards, e.g. DIN V 18599-10:2011.

1.2.2.5. Approaches for simplified LCA of buildings

A 100% complete, quantitative LCA has never been accomplished, nor is it likely to be (Graedel 1998, p.87). Since a full LCA can be time- and resource-intensive, it is necessary to use simplified methods (Hochschorner & Finnveden 2003, p.119). Simplified approaches are essential if one wants to include environmental aspects in a very early stage of product development (Fleischer & Schmidt 1997, p.20). To simplify the procedure for conducting an LCA, only the most relevant environmental aspects should be considered. Which aspects are relevant depends on the building type and other determining factors, such as intended use and climate: different aspects are relevant for a single-family house in Norway than they are for an office building in Dubai. Simplified LCA approaches are often called *screening LCA* or *streamlined LCA* (cf. Weitz et al. 1996, p.79; Hunt et al. 1998, p.36). Hochschorner & Finnveden (2003, p.128) compared simplified approaches and conclude they are valuable before conducting a full LCA.

To classify these simplified approaches, Wenzel (1998, p.281) distinguishes between three basic levels of LCA:

- A matrix LCA; qualitative or semi-quantitative (cf. Graedel 1996, p.3)
- A screening LCA; quantitative using readily available data or semi-quantitative
- A full LCA; quantitative and including new data inventory

Simplified approaches are especially important for the LCA of buildings, because buildings usually consist of many different products and materials, meaning that a full LCA is very difficult (Wittstock et al. 2009, p.9). A variety of simplified approaches for buildings can be found in the literature, e.g. Zabalza Bribián et al. (2009, p.2512), Bonnet et al. (2014, pp.4-7), Lewandowska et al. (2014, p.11).

To distinguish between different simplification approaches for the LCA of buildings, the EebGuide (Wittstock et al. 2012, p.30) introduces three categories with increasing levels of detail:

- Screening LCA
- Simplified LCA
- Complete LCA

The differences between the three types are summarized in Table 15.

Table 15: Summary of recommendations by EebGuide (Wittstock et al. 2012, pp.49-51)

	Screening LCA	Simplified LCA	Complete LCA
Number of indicators employed	At least 1 or two indicators	Reduced indicator set	A comprehensive set, e.g. list from EN 15978 or list from ILC Handbook
Type of data	Generic LCA data	Generic or average LCA data	Specific LCA data (EPDs)
Mandatory life cycle modules	A1-A3, B6, B7	A1-A3, B4, B6, B7, C3, C4, D	A1-A3, A4, A5, B1, B2, B3, B4, B5, B6, B7, C1, C2, C3, C4, D
Energy demand calculation method	Estimation of expected performance target	National calculation method or dynamic simulation	National calculation method or dynamic simulation
Mandatory building parts to be included	Roof, load-bearing structure, building enveloped including windows, floor slabs, foundation, floor finish-es/coverings	Roof, load-bearing structure, building enveloped including windows, floor slabs, foundation, floor finish-es/coverings	Roof, load-bearing structure, building enveloped including windows, floor slabs, foundation, floor finish-es/coverings, wall finishes/coatings, doors, building services including heating, cooling, lighting, escalators/lifts, water system

A range of building certification schemes employ simplified or screening LCA to evaluate environmental sustainability (see Table 16).

Table 16: Building certification schemes that employ LCA

Name	Country of origin	Type of LCA	Website
DGNB	Germany	Simplified	http://www.dgnb-system.de/en/
BNB	Germany	Simplified	https://www.bnb-nachhaltigesbauen.de/
HQE	France	Simplified	http://assohqe.org/hqe/
BREEAM	UK	Simplified	http://www.breeam.org/
Minergie Eco	Switzerland	Screening (primary energy only)	http://www.minergie.ch/minergie-ecop-eco.html
Verde	Spain	Simplified	http://www.gbce.es/pagina/certificacion-verde
LEED	US	Screening (3 indicators, structure and enclosure only)	http://www.usgbc.org/leed#v4

The role of LCA within building certification systems is illustrated here, using the 2015 version of DGNB[32] for residential buildings as an example. DGNB has two criteria for the LCA of the building: ENV1.1 for output-related impacts and ENV2.1 for the primary energy demand. Those two criteria are rated with 7.9% and 5.6% of the total credit points respectively, or 13.5% together, indicating that the LCA has a large significance for the overall rating. Water is not assessed within those criteria, but instead is covered in a separate one (ENV2.2). With the exception of *abiotic resource depletion,* DGNB incorporates all output-related indicators defined in EN 15978:2012. To compensate for neglecting certain small building components due to the simplification, DGNB adds 10% to the results at the end.

The individual indicators are then aggregated into so-called *check list points*. The aggregation is based on weighting each indicator. In contrast to Switzerland, where the method of ecological scarcity can be seen as a standard weighting method, Germany does not have a commonly agreed method. DGNB employs its own system and provides reference values for the normalisation of each indicator. Credit points are given for being below these values. These credit points are then weighted by factors and summed up, resulting in an overall score for these two criteria. The detailed calculation is described in Appendix B.

In their simplified approach, DGNB lists the nine following building components to be considered in the LCA:

1. Exterior walls (including windows and doors) and walls underground
2. Roofs
3. Ceilings (including covering and finishing)
4. Slabs (including covering and finishing)
5. Foundations
6. Interior walls and doors (including finishing and interior columns)
7. Building services for heating, ventilation, air conditioning (HVAC)
8. Other building services (e.g. photovoltaics or solar thermal collectors)
9. User equipment with significant energy demand in the use phase (e.g. cooling storage)

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[32] The DGNB criteria catalogue can be requested at http://www.dgnb-system.de/en/services/request-dgnb-criteria/ (accessed March 21st 2016)

Additionally, they note that all building services must be included in the model, but that pipes, cables, and additional equipment are omitted for point 7. An additional remark for points 8 and 9 states "if the environmental data is available". Point 9 is usually not relevant for residential buildings. To take into account missing data and uncertainties using this simplified assessment, DGNB multiplies the final LCA results by the factor 1.1.

The EeBGuide (Wittstock et al. 2012, pp.49–51) lists the same components, but only defines points 1 to 6 as mandatory for screening and simplified LCA. The assessment of all components is necessary for a complete LCA. BNB provides a similar list with identical points 1 – 5. Their point 6 refers to interior walls, point 7 to doors, and point 8 to heat generation plants.

According to El Khouli et al. (2014, p.48), the embodied primary energy of the primary construction and the building envelope make up 76% of the total embodied energy. In contrast, the interior outfitting and building service components only have a share of 14% and 10%. The interior outfitting is very dependent on the occupant, and is often replaced before the end of its reference service life (RSL), which introduces additional uncertainty. The embodied energy for building service components currently still plays a minor role for most residential buildings, which may change in the future as building automation becomes more common.

1.2.3. Summary of Section 1.2

Which steps are necessary to conduct an LCA, and what are the limitations of the LCA method?

LCA involves evaluation of the environmental aspects of a product or service through all stages of its life cycle. The most important characteristic of LCA is that results are always based on a functional unit (König et al. 2009, p.40). A further key characteristic is the definition of a system boundary representing the border between the technosphere and the natural environment. According to ISO 14040:2009, LCA consists of four main steps:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation

The limitations of LCA have to be clear for its application to be useful. LCA results are not able to predict precise or absolute environmental impacts, but only potential impacts. Further limitations are the independence of time and place, limited impact categories, and the need for assumptions to carry out an LCA. These assumptions are one reason for high uncertainties in the LCA results, in addition to uncertainties due to input data and the characterization models.

What are the most important parameters to characterize LCA for buildings?

The European regulations for LCA for buildings – EN 15978:2012 and EN 15804:2012 – divide the building's life cycle into five main stages: production, construction, use, end of life and benefits and loads beyond the system boundaries. A particularity of LCA for buildings is that the use phase of buildings can range from 30, to 50, to over 100 years, making the operational energy demand calculation an important parameter. The building's operational energy demand can be calculated by means of *dynamic building performance* simulation (DBPS) or *quasi-steady state methods* (QSSM). In contrast with common product LCA, most LCA studies for buildings use predefined LCIA data, which can be found in databases, such as ökobau.dat, or environmental product declarations (EPDs). Data availability has improved in recent years, however not all building materials are included in databases. To simplify the LCA process, various approaches have been developed based on the idea of only assessing the most relevant aspects. EebGuide (Wittstock et al. 2012, p.30) classifies them in three categories with increasing level of detail: screening LCA, simplified LCA, and complete LCA. The simplified LCA corresponds to the level of detail required for building certification systems. The functional unit for LCA for buildings is usually defined as to 1 m² of net floor area and 1 year of operation.

1.3. Architectural design

This section provides essential background knowledge for the computational approaches in the following methods chapter. It is divided into four parts: the first one describes the stages of the architectural design process related to LCA, the second one briefly shows why architects employ *computer-aided design* (CAD) in the design process, and the third one explains the concept and characteristics of *parametric design.* The potential for design optimization inherent in a parametric approach is described in the fourth part.

1.3.1. Stages of the architectural design process

In most industrialized countries, the architectural design process is divided into several stages which serve as a basis for regulations and for the calculation of architects' fees. For this thesis, the structure described by El Khouli et al. (2014, p.68) is employed, which divides the design process into six stages, namely:

1. Preliminary studies
2. Concept design
3. Developed design
4. Technical design
5. Construction
6. Use

Table 17 lists typical tasks and aligns these six stages with examples of national fee structures.

Table 17: Stages in the architectural planning process

Stage	1 Preliminary studies	2 Concept Design	3 Developed Design	4 Technical Design	5 Construction	6 Use
Typical tasks	Feasibility studies, call for competition	Concept, sketches, competition design	Elaboration of design, building permit	Detailed planning, procurement	Construction surveillance	Hand over, operation
HOAI (Germany)	1	2	3, 4	5, 6, 7	8	9
SIA 102 (Switzerland)	11, 21, 22	31	32, 33	41, 51	52, 53	61,62
Loi MOP (France)	ESQ	AVP, APS	APD, PRO	EXE, DCE	DET	AOR
RIBA 2013 (GB)	0, 1	2	3	4	5	6, 7
AIA (US)	PR	SD	DD	CD, PR	CA	OP

The design process begins with preparation in stage one, which consists of preliminary studies, research, feasibility studies, and the definition of project roles. For architecture competitions, this work is usually carried out by the competition initiators, and the information is provided to the participants.

In the second stage, a basic architectural concept is developed. This is where the most fundamental decisions are made, including the number of storeys, orientation, and building massing. The level of detail corresponds to the requirements of most architectural competitions. LCA would be a valuable tool for competition juries to evaluate the environmental impact of design proposals, if the effort required was less intensive (Fuchs et al. 2013, pp.97-99).

In the third stage, the design is refined and the final geometry is determined. The materials of the primary construction and the building envelope are defined in a generic way. While the general choice of material is known, e.g. concrete, its precise quality characteristics and manufacturer are not yet decided. The application for a building permit usually follows this phase.

In the fourth stage, design details are drawn up and technical specifications are defined. Tendering and procurement are carried out at the end of this phase. The bill of quantities (BOQ) can be established afterwards. Only after procurement are details about the manufacturers known, and specific EPDs can be employed for LCA if available.

Stage 5 is the construction of the building culminating in stage 6, the handover of the building to the client. A large part of the operational demand has already been defined in the design process, for example by the thermal quality of the building envelope, the window layout, and the choice of heating and ventilation systems. Nevertheless, the user's behaviour also influences energy consumption to a certain degree (Hegger et al. 2007, p.189), such as through the temperature that tenants set in their rooms.

Decisions made in the early stages of the design process, namely stages 1 and 2, have the greatest influence, as they set general conditions for the subsequent planning process (see Figure 14). As such, they not only have the largest impact on the costs (Paulson Jr. 1976, p.588), but also on both operational energy demand (Hegger et al. 2007, p.180) and the resulting operational and embodied environmental impacts (Schneider 2011, p.39). The cost of design changes is lowest in the early design stages. Consequently, design optimization is best achieved in these stages.

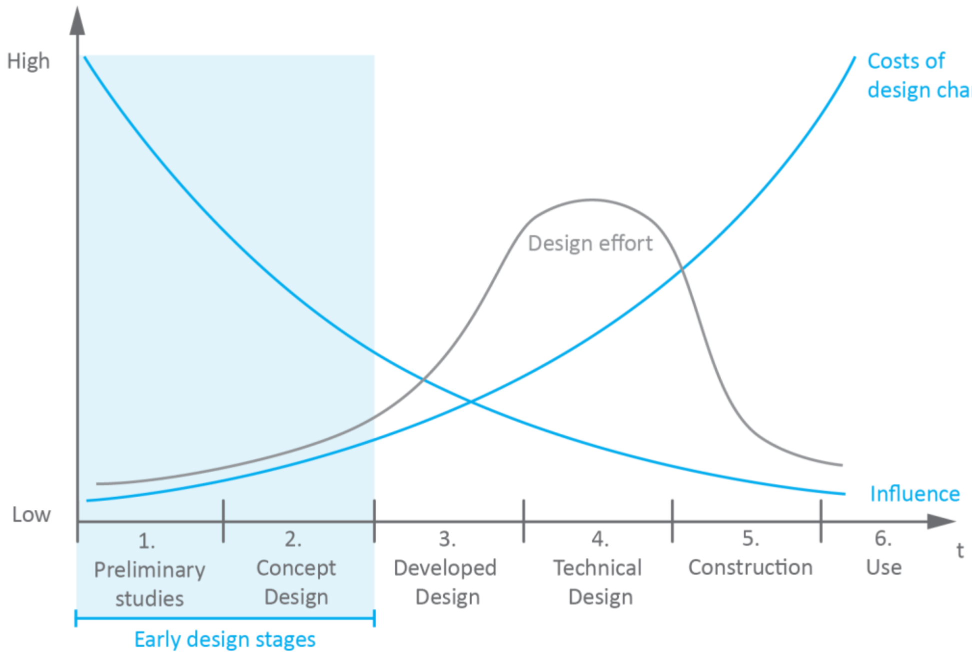

Figure 14: 'Paulson curve' (Paulson Jr. 1976, p.588)

The dilemma inherent in undertaking LCA during the design process is that, while decisions taken in stage 2 have the greatest influence, the information available is scarce and uncertain. The exact BOQ and product-specific information needed for a complete LCA is only available after stage 4. By then, the LCA results are less useful because it is too costly to make significant changes at that stage. Basically, once the necessary information is available, the LCA results are impractical to implement.

1.3.2. Computer-aided design

Computers are commonly employed throughout all stages of the architectural design process. Based on a survey of 319 architects, Weytjens et al. (2009, p.293) report that 80% of architects use computer-aided design (CAD) as a design support tool. CAD can be defined as the use of computer systems to aid in the creation, modification, analysis, or optimization of a design (Lalit Narayan et al. 2008, p.3). According to Weisberg (2008, p.3:1), the first graphical programming took place at MIT in the 1950s. The first programme to draw using a computer was published by Ivan Sutherland in 1963 as part of his Ph.D. thesis (see Sutherland 1963). It was called *Sketchpad* and can be seen as the ancestor of CAD programmes.

It did not take long until developments of computer modelling pointed out the advantages of an integrated representation of the building. Before computers were employed, architects used drawings and physical models for representation of their design. Both share some disadvantages that the computer solved. For example, multiple drawings or models were needed to represent different levels of detail in different scales. This meant laborious work and high costs, especially when changes occurred (Eastman 1975, p.46). The use of computers facilitates adapting to changes, as well as the copying and distribution of plans. However, CAD only became widely used in practice once personal computers (PCs) became affordable in the middle of the 1980s (Weisberg 2008, p.13:7)

At that time, CAD was used in various disciplines, such as design, engineering, and architecture. As more and more programs became available, the term *computer-aided architectural design* (CAAD) was introduced to describe programmes with functions relating especially to architecture. The concept is the same, therefore, in the context of this thesis: no distinction between CAD/CAAD is made.

At the beginning, CAD models were primarily intended as representations of geometric information. It did not take long to recognize that if geometric information could be integrated, non-geometric information could be integrated as well (Citherlet 2001, p.15). Most analyses, such as cost estimation, require numerical information, which had to be extracted manually from drawings, resulting in a high level of effort and high costs (Eastman 1975, p.46). Eastman et al. (1974, p.5) describe their *Building Description System* as an ideal computational representation of a building with integrated numerical information of building parts. This development finally led to what today is called *Building Information Modelling*. The term BIM refers to both the method of Building Information Modelling and the actual Building Information Model itself[33]. Besides the 3D representation of geometry, the model can include all kinds of information, such as physical properties, costs, or manufacturing data of components.

1.3.3. Parametric design

Most architects use 2D CAD programmes to draw the same way they would draw with a pencil on paper. Once drawn, the geometry is fixed and changes in the design require redrawing the initial geometry. As such, changes to the design and the generation of alternative design variants involve a high level of effort. A development that avoids this

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[33] According to the National BIM standard, a Building Information Model (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle.
(https://www.nationalbimstandard.org/faqs#faq1, accessed March 21st 2016)
According to Lee et al. (2006, p.758), BIM is the 'process' of generating and managing building information in an interoperable and reusable way.

effort has become popular in the last decade: *parametric design*. The basic idea is to describe the geometry using parametric equations. These are defined as "set of equations that express a set of quantities as explicit functions of a number of independent variables, known as 'parameters'" (Stover & Weisstein 2015, p.1). The geometry is based on these defining parameters, such as width, height and length for a cube (see Figure 15). These parameters can easily be changed afterwards, making it possible to quickly vary the basic form.

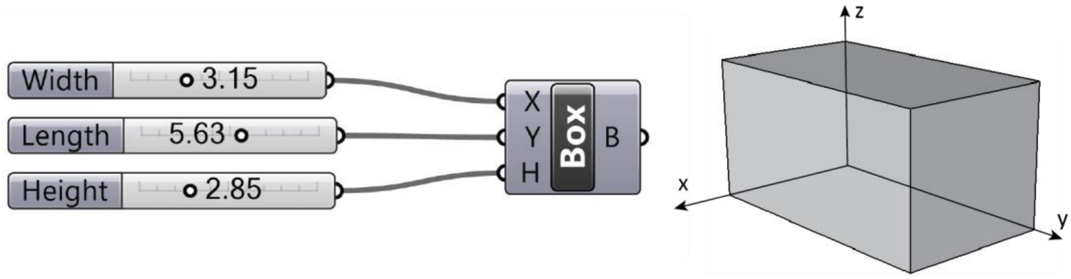

Figure 15: Parametric definition of a cube with number sliders

The recent availability of computer tools has promoted its wide application in architecture and design, but parametric design has been known for a long time (Davis 2013, p.18). Davis (2013, p.19) found the earliest documentation of parametric design in James Dana's description of drawing crystals (Dana 1838, p.41). In 1960, Luigi Moretti held a *Parametric Architecture* exhibition in Milan showing a parametric stadium design, amongst others (Bucci & Mulazzani 2002, p.114). The first CAD software, published in 1963, was parametric (Woodbury 2011, p.11). The designer could draw lines and arcs using a *'light pen'*, which could then be related to one another, which Sutherland (1963, p.9) called *atomic constraints*. He never called them *parametric*, but according to Davis (2013, p.4), each of these constraints had a set of outcomes expressed as an explicit function of a number of independent parameters and the software therefore meets the definition of a parametric process.

The first viable parametric software used in practice was released in 1987 and called *Pro/ENGINEER* (Weisberg 2008, p.16:5). The software was designed for application in engineering, and the development of parametric software in architectural practice only started in 2003. The software was later released as *Generative Components* in 2007. In the same year, David Rutten released *Explicit History* which later was named *Grasshopper*[34]. *Grasshopper* has a visual programming interface, which has been appropriated and implemented in a similar way for other parametric tools, such as *Dynamo*[35], which is based on the BIM-software *Revit*[36].

In addition to the geometry, parameters for non-geometric information such as material properties can be parametrically varied too. Each numerical input can be realized via a so-called *number slider* (see Figure 15). Design variants can be generated through 'sliding' the *number slider*. This process can be employed for optimization of the design, either intuitively by the architect through manual variation, or through the application of computational optimizers.

One main advantage of the parametric approach is the possibility to easily generate numerous different design variants. Simon (1996, p.121) hypothesises that the logic of design is concerned with finding alternatives and making a rational choice between them. Lawson (1994, p.138) observed that many designers express a need to generate and assess alternative design ideas. With the help of a parametric model, the architect can fulfil this need. Once a parametric model has been developed, the generation of further design alternatives is nearly effortless.

While some designers deliberately generate a series of alternative solutions early on, others prefer to work on a single idea, but accept that it may undergo revolution as well as evolution (Lawson 2006, p.154). This approach implies that many changes to the initial design are made. According to Davis (2013, p.34), the real benefit of parametric description comes from the low cost of the design changes. In the typical design process, deadlines are short and often impede time-consuming changes. Samuel Geisberg, the founder of *Parametric Technology Corporation,* which invented *Pro/ENGINEER*, calls the ability to adapt to changes '*flexibility*'. His goal was to create a system that is flexible enough to easily consider a variety of designs, while the cost of making design changes should be as close to zero as possible (Teresko 1993, p.28).

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[34] Grasshopper3D is a graphical algorithm editor for 3D CAD software Rhinoceros and can be downloaded at http://www.grasshopper3d.com/page/download-1 (accessed March 14th 2016)

[35] Dynamo is an open source graphical programming for Autodesk Revit, see http://dynamobim.org/, (accessed March 21st 2016)

[36] Revit is a BIM software developed by Autodesk http://www.autodesk.com/products/revit-family/overview (accessed March 21st 2016)

Paulson Jr. (1976, p.588) first described the course of costs throughout the design process as shown in Figure 14. In consequence of the high costs for changes in later stages, various initiatives aim to integrate more decisions into the early design stages, e.g. *Integrated Project Delivery (IPD)*[37]. The intention is to 'shift forward' the design effort into earlier design stages to reduce costs (AIA 2007, p.21). MacLeamy presented a graph in 2004 showing two additional curves (CURT 2004, p.4) (see Figure 16). The effort of a traditional design is greatest during stage 4, while IPD shows the greatest effort in stage 2.

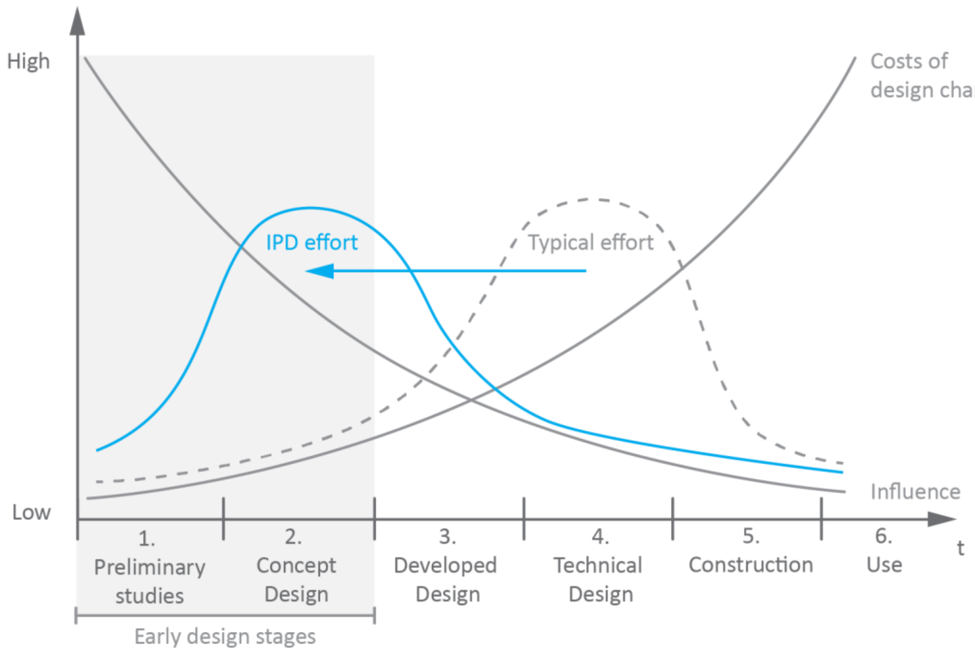

Figure 16: 'MacLeamy curve' (CURT 2004, p.4)

In contrast to shifting the design effort into early stages, Davis (2013, p.36) proposes using parametric models in order to be flexible enough to make decisions later, without additional costs. As such, he sees an adjustment to the form of the original curves by Paulson (see Figure 14) rather than a shift in the design effort (see Figure 17). He argues that some changes can be anticipated, but others are inevitable because they come from forces outside the designer's sphere of influence: for example, the client can change the brief, politicians

[37] Integrated Project Delivery (IPD) is a project delivery method that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction (AIA CC 2014, p.4).

can change legislation, or market forces can change the price of materials. Therefore, it is important to be flexible to adapt to those changes.

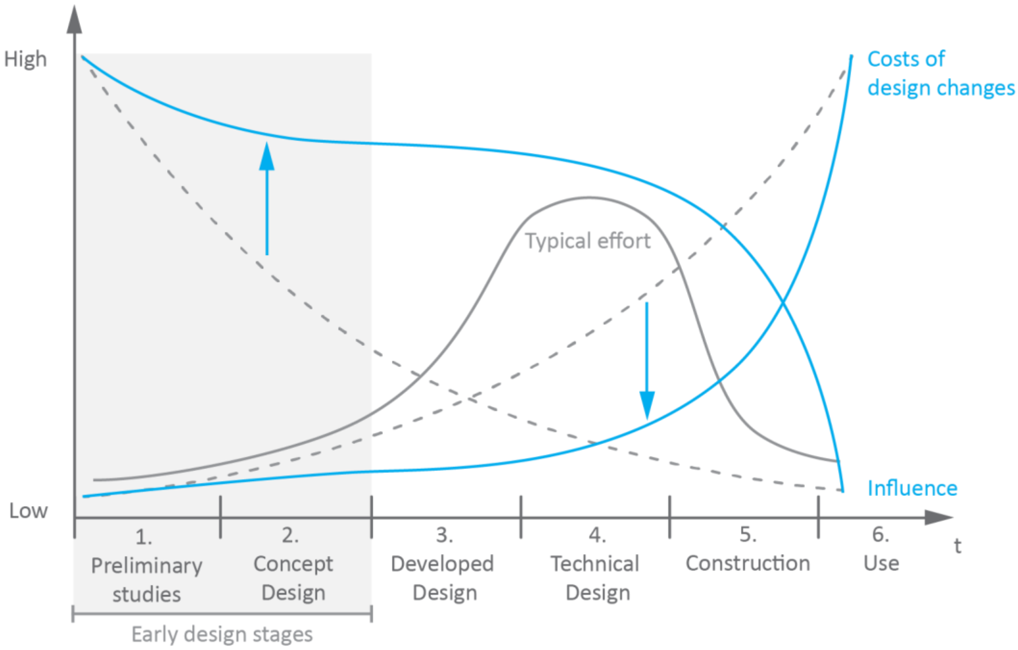

Figure 17: 'Davis curve' [38]

Parametric design supports and facilitates both approaches: shifting decisions into early design stages (stage 2) is made possible through the comparison of many variants quickly generated by the parametric approach, and the ability to adapt quickly to changes also provides the flexibility to make decisions later (stage 4) without incurring higher costs.

The advantages of parametric description can be summarized in two main points: First, the design can be easily adapted to changes, reducing effort and costs. Second, design variants can be generated quickly, which corresponds to the architects' need for alternatives and serves as the basis for optimization processes. This is illustrated in the next section.

1.3.4. Optimization approaches in architectural design

The design variants provided by the parametric approach can be used as the basis for optimization. Parametric design allows for very quick generation of design solutions, but for time-efficient optimization, methods for quick analysis are needed as well. Optimization

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[38] This curve is described and displayed on Davis' blog: http://www.danieldavis.com/macleamy/ (accessed December 12th 2015)

using analysis methods in architecture is an iterative process, and consists of four general steps: parameter input, the calculation itself, output of the results, and the optimization (see Figure 18). In step 4, the output is evaluated to check if it meets the goals for the analysis. If that is the case, the process ends and a solution has been found. If it is not the case, the input parameters are adjusted, and the loop is run iteratively until the goal has been achieved.

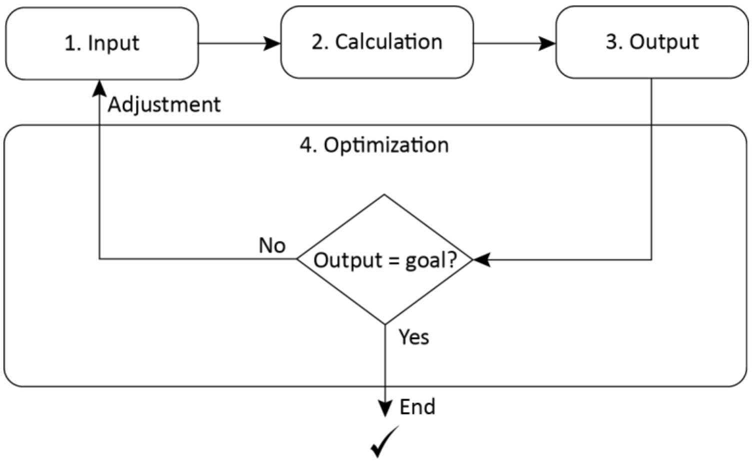

Figure 18: General optimization steps

In general, a distinction between two approaches for design optimization is made: architects can either manually vary parameters and improve the design iteratively, or apply computational optimizers. Quantitative criteria, such as a certain energy demand that the building design should meet, can be evaluated numerically. However, design characteristically also involves making judgements between alternatives that cannot be reduced to a common metric, and therefore require the subjective evaluation of the designer (Lawson 2006, p.298).

In the first approach, the architect manually generates different variants and then compares them to find those that indicate better performance. The architect can successively improve the design in an iterative process. The architect can influence the performance of the design using two fundamental parameters: geometric parameters such as building size, orientation, or window layout, and non-geometric parameters, namely building materials and building services. Manually changing the design allows the architect to consider additional boundary conditions and further qualitative aspects such as aesthetic appearance.

The second approach employs algorithms that automatically generate variants. For the optimization towards quantitative criteria, computational solvers can be employed and linked to the parametric model. There are a range of computational optimizers that can be employed for architectural design problems. In addition to precise analytical approaches, heuristic approaches, such as evolutionary algorithms (EA), are commonly employed. These algorithms *'mimic'* biological evolution, namely, the process of natural selection and the *'survival of the fittest'* principle (Pintér & Weisstein 2015, p.1). They require only little background knowledge about the problem and are therefore suited for complex problems, where an analytical solution isn't possible or is too intricate (Weicker 2002, p.42). As such, they are adequate for design problems where the problem definition underlying the design proposal is not clearly defined at the beginning.

When using EA, the free parameters that should be varied, called *genes*, are assigned to the optimizer. The objective function for the optimization is often called the *fitness function*. In the example of optimization for minimum energy demand, the fitness function could equal the minimization of the energy demand per floor area. The EA starts the optimization process by generating a certain number of candidate solutions, called the *population*, through random variation of the genes. These individuals form the first *generation*. Each individual of the first generation is evaluated and assigned a *fitness value*. The solutions with poorer fitness values are dropped. The remaining pool of candidates with higher fitness values are recombined with other solutions by swapping components with another and/or mutated by making some smaller-scale changes to a candidate (see Coello et al. 2007, pp.24-29). This process is repeated until a termination condition is reached, such as a maximum number of generations.

Most architectural and engineering problems are multi-objective optimization problems (Coello & Christiansen 1999, p.337). To optimize for more than one objective and find the trade-off between conflicting objectives, evolutionary multi-criteria optimizers (EMO) can be employed. When the solutions of bi-objective optimizations are plotted in a graph, a curve called *Pareto-front* can be seen (see Figure 19). The solutions on the curve are *Pareto-optimal,* meaning they cannot be improved for one criterion without performing worse for the other criterion. This approach can also be employed for multiple objectives. The visualization of a multi-dimensional Pareto-front becomes difficult, but various methods have been developed, ranging from dividing it into separate *level diagrams* for each objective and design parameter (Blasco et al. 2008, pp.3909-3911) to 3D virtual reality (Madetoja et al. 2008, p.907).

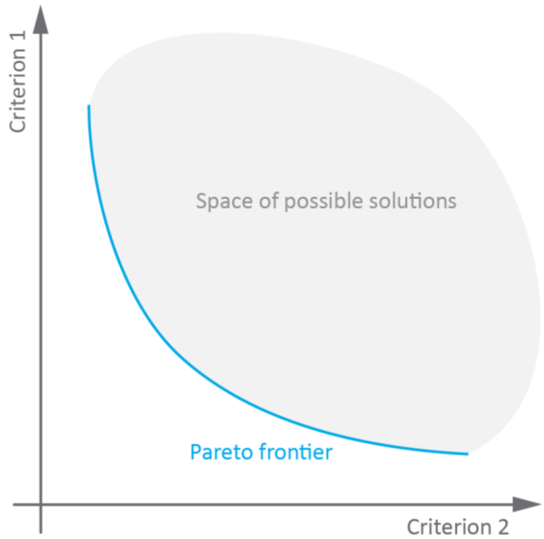

Figure 19: Pareto-front

In contrast to well-defined problems with an apparent goal and end, Rowe (1987, p.40) describes architectural design problems as ill-defined, where both the end and the means for solution are unknown. Subsequently, many alternative solutions may exist and design becomes a process of selecting amongst them. Solutions that are proposed are not necessarily correct or incorrect (Rittel & Webber 1973, p.163), and plausible alternative solutions can always be provided (Rowe 1987, p.41). The designer has to decide when a proposed solution is good enough (Rittel & Webber 1973, p.162). Simon (1996, p.119) introduced the term *satisficing* to describe this kind of solutions which are good enough but not necessarily optimal. When employing heuristic optimizers, such as EA, the optimization process stops when reaching a termination condition, such as a run time limit. The designer cannot be sure that the global optimum has been found, but only trust that the EA had 'enough time' to be able to find a solution close to the global optimum.

According to Rittel (1992, pp.75-92), a vast design space has to be explored to find the optimum solution. He describes different types of approaches to explore the design space. The first is the linear approach of a designer who is sure to make the right decision based on his experience and intuition, and therefore only provides one solution in every design stage (see Figure 20a). The second approach describes a designer who generates and evaluates design alternatives. After deciding on the best solution, this designer moves on to the next stage, to generate alternatives again (see Figure 20b). In this way, the designer tries to find the best solution, however, he can never be sure whether an alternative solution dropped in a prior stage could have ended up as the best solution after passing through more stages. Therefore, according to Rittel (1992, p.80), a multi-stage alternative generation would be best to provide a basis for decisions. He exemplifies this idea with a chess-player who plans some moves ahead for each possible next move. As a result, a decision tree emerges (see Figure 20c).

This is also true for the application of LCA during the design process. If the architect develops a number of geometric variants and decides on one geometry, then provides a number of material variants and decides for one material, etc., the decisions are based on educated guesses, because the LCA can only be carried out at the end of the process when all parameters have been defined. Ideally, the possible next steps following the first decision would be carried out for all variants providing a tree of possible solutions for decision-making.

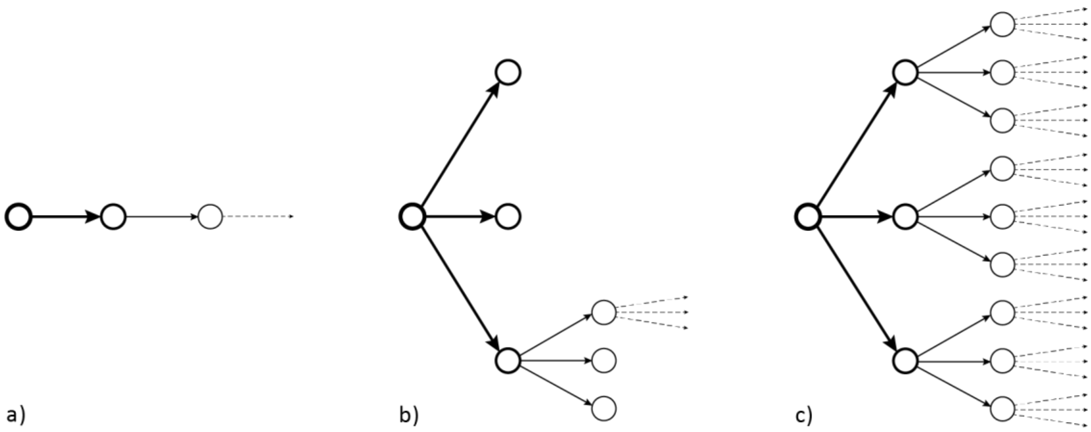

Figure 20: Linear process (a), process with variants (b) and decision tree (c), based on Rittel (1970, pp.78-81)

1.3.5. Summary of Section 1.3

Which are common stages of the architectural design process and their relation to LCA?

In most industrialized countries, the architectural design process is divided into several stages. For this thesis, the structure by El Khouli et al. (2014, p.68) is employed, which divides the design process into six stages, namely:

1. Preliminary studies
2. Concept design
3. Developed design
4. Technical design
5. Construction
6. Use

Decisions made in the early stages of the design process, namely stages 1 and 2, have the greatest influence on costs (Paulson Jr. 1976, p.588) and environmental impacts (Schneider

2011, p.39). As such, design optimization is best achieved in these stages. The dilemma inherent in undertaking LCA during the design process is that decisions taken in stage 2 have the greatest influence, but the information available is scarce and uncertain. Information needed for a complete LCA is only available after stage 4. By then the LCA results are less useful, because it is too costly to make significant changes at this stage. Basically, once the necessary information is available, the LCA results are impractical to implement.

What have been the most important developments in computer-aided design and which main benefits do they provide for architects?

Computer-aided design (CAD) can be defined as the use of computer systems to aid in the creation, modification, analysis, or optimization of a design (Lalit Narayan et al. 2008, p.3). In comparison with the paper plans and models used previously, the use of computers not only facilitates adapting to changes, but also copying and distributing plans. Besides being representations of geometric information, today, CAD models incorporate non-geometric information, such as material properties or costs, which is called *Building Information Modelling* (BIM).

What are the main characteristics of parametric design, and which main benefits does is it provide compared to conventional CAD?

The basic idea behind parametric design is to describe a geometry using parametric equations. The geometry is based on these defining parameters, which can easily be changed afterwards. In addition to the geometry, parameters for non-geometric information, such as material properties, can be varied, too. As such, parametric design facilitates shifting decisions into early design stages (stage 2) and also provides the flexibility to make decisions later (stage 4) without inducing higher costs. The parametric approach provides the opportunity to easily generate numerous different design variants, which corresponds to the architects' need for alternatives and serves as the basis for optimization processes.

Which general approaches to design optimization can architects use?

Design optimization is an iterative process of generating, evaluating, and comparing design variants. Usually, architects can influence two main parameters of the design: first, the geometry, and second, building materials and services. In general, a distinction between two approaches for design optimization is made: architects can either manually vary parameters and improve the design iteratively, or apply computational optimizers. The quick generation of variants using parametric design allows for both approaches.

1.4. Analysis of existing approaches

This section consists of three parts. The first part explains the challenges for the LCA of buildings and especially for its integration in the design process. The second part analyses existing commercial and academic approaches for the LCA of buildings. In addition, existing approaches to integrating energy demand calculation into the design process are analysed. The third part summarizes the analysis and illustrates the research gap.

1.4.1. Challenges for LCA in the architectural design process

In comparison to the LCA of consumer products, there are a number of challenges when conducting LCA of a building (Khasreen et al. 2009, p.677). Here, they are divided into four main challenges:

1. Buildings usually consist of different building components, each consisting of many different materials, which makes the manual establishment of a bill of quantities (BOQ) a laborious task. "The extent of information necessary to carry out a life cycle assessment is immense." (Finch 1994, p.1437).
2. Buildings possess a very long life span with a use phase that can easily last more than a hundred years.
3. Buildings may undergo many significant changes in form and function during their life span. These changes are nearly impossible to predict, introducing a high degree of uncertainty.
4. The end-of-life scenario is also very uncertain. Most consumer products are produced by a single manufacturer, who can take back the product and recycle it or dispose of it in a controlled way, as its constituent parts are known. For the construction of buildings, different trades assemble different products made by different manufacturers. In addition, these are often inseparably connected. This hinders the return of components to the manufacturer and makes recycling difficult.

When conducting LCA during the design process, additional challenges arise. As noted in Section 1.3.1, the dilemma of LCA during the design process is that it has the greatest influence when carried out in stage 2, but the necessary information is only available after stage 4, once the LCA results are already impractical to implement. Even if the necessary information is available beforehand, LCA is not sufficiently integrated into the architectural design process (Hildebrand 2012, p.72). Various explanations can be found in the literature: Baitz et al. (2012, p.6) describe the general discrepancy between the application of LCA in a scientific context and in practice and show the demand for practical tools. Bates et al. (2013, p.1) state that no efficient means for LCA during the design process currently exists.

According to Zabalza Bribián et al. (2009, p.2512), the current, excessively complex calculations for LCA result in high costs. Furthermore, LCA is not covered within the standard fee structure for architects and must be commissioned separately, resulting in further costs for the client (Weißenberger et al. 2014, p.554).

In the few cases where the LCA of a building is conducted in practice, the LCA is required for a building certification system. However, evaluating the building design through LCA is not sufficient on its own, as it does nothing to improve the design (Wittstock et al. 2009, p.4). In order to minimize environmental impacts, an optimization is needed. Further challenges arise in the optimization process. First of all, most buildings are unique designs, meaning the parameters that influence their energy performance vary from building to building. This makes every kind of optimization difficult when compared with a serially produced product. For consumer products, a lot of time can be invested in finding the optimal solution, because even a very small improvement in the individual product has a great impact when multiplied by the vast number of products sold. In contrast, only a limited effort can be spent on optimization of unique buildings. Second, deadlines in the design process are usually very short. Therefore, the optimization results must be provided quickly, making very time-efficient optimization methods necessary. The demand for a time-efficient method for the LCA of buildings is clearly stated in an article in the *International Journal of Life Cycle Assessment,* written by 22 experts, including practicing professionals and researchers:

> *"In practice, LCA results produced in-time that point >80 % in the right direction are improving applications whereas a "100 %" solution, which can't stick to any deadline does not have any impact in the real world"*
> *(Baitz et al. 2012, p.13).*

Third, the numerous design parameters, such as geometry, building materials, and building services influence each other. The optimum insulation thickness depends on the specific geometry and the heating system employed, for example. Changing one of those parameters can lead to very different results. The separate optimization of an individual aspect is therefore impractical. As such, all these parameters have to be included in the optimization process in order to guarantee holistic solutions.

1.4.2. Existing computer-aided LCA approaches for buildings

Various computer-aided approaches for the LCA of buildings exist. In the following section, these tools are assessed with regards to their applicability in the architectural design process. For all of the approaches, the workflow consists of input, calculation, output, and in the case that an optimization is carried out, a fourth step: optimization (see Section 1.3.4). Academic approaches found in the scientific context differ from those in practice and are therefore considered separately. Furthermore, existing approaches to integrate energy demand calculation in the design process are discussed, as operational energy demand is important for LCA and is currently calculated separately.

1.4.2.1. Commercial tools

Overviews and comparisons of commercial tools can be found in Zabalza Bribián et al. (2009, p.2512), El Khouli et al. (2014, p.69), and Lasvaux et al. (2012, p.9). In 2005 a report benchmarking eight tools for the LCA of buildings was published (see Peuportier & Putzeys 2005), but most of these tools are not available anymore or have been modified. Table 18 gives a non-exhaustive overview of currently available computer-aided LCA tools. Each tool follows a slightly different approach, with different data sets (Lasvaux & Gantner 2013, p.407). To structure the evaluation of the main tools, they are categorized into four groups according to their main characteristics. The four categories are described in the following to illustrate their fundamental differences.

1. **Generic LCA tools:** Generic LCA tools, such as *GaBi*[39], *Sima Pro*[40], or *OpenLCA*[41]have been developed for the LCA of products or processes. The products are modelled using elements and flows, and the tools provide detailed functions and many different characterization models. The input occurs manually in tabular form. These tools are commonly employed to create EPDs for building materials. Wittstock et al. (2009, p.6) conducted a LCA of a building using a generic model in GaBi. Apparently, this approach has not been pursued further and the GaBi developer *Thinkstep* now recommends using *SBS onlinetool*[42], an online catalogue, for the LCA of buildings.
2. **Spreadsheet-based calculation:** Most tools specified for the LCA of buildings are based on the manual input of the bill of quantities (BOQ) in a spreadsheet. The embodied impact is calculated by multiplying the mass of the building materials with their respective environmental impact factors, which is integrated into the tools.

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[39] GaBi is an LCA software developed by thinkstep, see http://www.gabi-software.com/international/index/ (accessed March 2nd 2016)

[40] SimaPro is developed by PRé and can be obtained at https://www.pre-sustainability.com/simapro (accessed March 2nd 2016)

[41] OpenLCA is an open source LCA software and can be downloaded at http://www.openlca.org/downloads (accessed March 2nd 2016)

[42] SBS online tool is provided by Fraunhofer Institute for Building Physics (IBP) and thinkstep, https://www.sbs-onlinetool.com/ (accessed March 6th 2016)

Some tools, such as *Athena Impact Estimator*[43], allow for integration of the operational environmental impact, but the user has to manually input the externally calculated energy demand. *LEGEP*[44] and *Elodie*[45] are exceptions to this, as they can internally calculate the operational demand.

3. **Online component catalogues:** Various online catalogues are available to facilitate the LCA of building components, such as the *Bauteilkatalog*[46], *eLCA*[47], and *SBS-onlinetool*. The catalogues are based on manual input of the quantities, from which a BOQ is generated and multiplied with the respective environmental impact factors. Typical components are predefined and can be modified quickly. In some cases, an externally calculated operational demand can be integrated.
4. **BIM-based tools:** Recently, a number of commercial plug-ins with links to BIM software have been published. The BOQ is generated automatically from the BIM and combined with the environmental data. However, the matching of material names in BIM with the environmental data can cause difficulties in practice (Reitschmidt & Díaz 2015, p.F5-5). Some tools only calculate the embodied impact, e.g. *TALLY*[48], and the operational energy demand has to be calculated using other plug-ins. *Lesoai*[49] and *optimi360*[50] can also calculate the operational impact and can therefore assess all life cycle modules required for building certification.

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[43] Athena Impact Estimator is a free LCA tool for buildings provided by Athena Sustainable Materials Institute. The software can be downloaded at http://calculatelca.com/ (accessed March 6th 2016)

[44] LEGEP is a German software developed by Holger König, see http://legep.de/ (accessed March 6th 2016)

[45] Elodie is a French software provided by the Centre Scientifique et Technique du Bâtiment (CSTB), see www.elodie-cstb.fr/ (accessed March 6th 2016)

[46] Bauteilkatalog is provided by Swiss Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (KBOB) and can be accessed at http://www.bauteilkatalog.ch (accessed March 6th 2016)

[47] eLCA is a free German online tool provided by Bundesinstitut für Bau-, Stadt-und Raumforschung (BBSR) and can be accessed at http://bauteileditor.de/ (accessed March 6th 2016)

[48] Tally is a plug-in for the BIM software Autodesk Revit and can be downloaded at http://choosetally.com/ (accessed March 6th 2016)

[49] Lesoai is an LCA tool for Switzerland, Germany and Luxembourg and provided by E4tech, see http://www.lesosai.com/en/index.cfm (accessed March 6th 2016)

[50] 360optimi is a LCA tools with plugins for major BIM software based on the IFC standard. It is developed by Bionova Ltd. see https://www.360optimi.com/ (accessed March 6th 2016)

These four categories are evaluated according to their applicability in the architectural design process:

- Generic LCA tools require extensive background knowledge and are therefore not suitable for non-LCA-experts.
- With the exception of BIM-based tools, all of the tools require manual input, which means extra effort to input the building geometry. Furthermore, input errors, such as missing components, are easily overseen.
- Some tools provide online access, which has the advantage that environmental data can be updated continuously in the background.
- As Table 18 shows, most tools only calculate the embodied impact and require external calculation of the operational energy demand. In this case, the operational energy demand is not linked to the thermal quality of the building envelope. A change in the material of the envelope, for example switching the insulation to another material with a different conductivity, causes a change in heating demand. A new external calculation has to be undertaken and the results have to be imported again. The effort this process involves means that users are unwilling to investigate more variants than absolutely necessary, and as such do not exploit the optimization potential.
- BIM-based tools have an automated take-off of the BOQ and therefore do not require manual input of areas and masses. In theory, the embodied impact can easily be calculated. In practice, the challenge lies in the high complexity reached by the BIM. In consequence, big projects require a means of managing BIM, while for small projects it is usually not employed at all. This complexity again reduces the likelihood of modelling various design proposals for optimization. Furthermore, the detailed level of modelling requires detailed information, which is usually not available in the early stages of the design process.

In addition to these issues, Table 18 indicates that there is no tool which has a link to a 3D model, calculates operational energy demand and embodied impact, and allows for optimization. The lack of an opportunity for optimization is the largest issue. Without optimization, the LCA does not have any real significance, since the environmental impact of the building is not reduced.

Table 18: Current computer-aided LCA tools

Type	Name	3D model	Energy demand	Embodied impact	Optimization	Online / Offline	Country	Website
Generic	Gabi			●		Off	Germany	www.gabi-software.com/software/
	SimaPro			●		Off	Netherlands	www.pre-sustainability.com/simapro
	OpenLCA			●		Off	Germany	www.openlca.org/
	Umberto			●		Off	Germany	www.umberto.de/en/
Spreadsheet-based	Envest 2*			●	○	On	UK	www.envest2.bre.co.uk/index.jsp
	SBS Building Sustainability		○	●		On	Germany	www.sbs-onlinetool.com
	Ökobilanz Bau		○	●		On	Germany	www.oekobilanz-bau.de/oekobilanz/
	eTOOL		○	●		On	Australia	www.etoolglobal.com/about-etoollcd/
	Athena Impact Estimator		○	●		Off	Canada	www.athenasmi.org/our-software-data/overview/
	EcoBat		○	●		Off	Switzerland	www.eco-bat.ch/
	Legep		●	●	○	Off	Germany	www.legep.de/
	novaEquer		○	●		Off	France	www.izuba.fr/logiciel/novaequer
	Elodie		●	●		Off	France	www.elodie-cstb.fr/
	GreenCalc+			●		Off	Netherlands	www.greencalc.com/index.html
Comp. catalogues	Eco2soft			●		On	Austria	www.baubook.info/eco2soft/
	Bauteilkatalog			●		On	Switzerland	www.bauteilkatalog.ch/
	eLCA		○	●		On	Germany	www.bauteileditor.de/
	BEES			●		On	US	www.nist.gov/el/economics/BEESSoftware.cfm
BIM-based	Impact	●	○	●		On	UK	www.impactwba.com/index.jsp
	Cocon-BIM	○	●	●		Off	France	www.eosphere.fr/
	Lesosai	○	●	●		Off	Switzerland	www.lesosai.com/de/index.cfm
	360optimi	●	●	●		Off	Finland	www.360optimi.com/en/home
	Tally	●	○	●		Off	US	www.choosetally.com/

○ Partial functionality / additional software needed / external calculation
● Full functionality
* No new licenses sold, now integrated in Impact

1.4.2.2. Academic approaches

Academic approaches to integrating LCA into the architectural design process mainly focus on BIM. The basic concept behind combining BIM and LCA can be found in Neuberg (2004, p.94) and Ekkerlein (2004, p.70). Seo et al. (2007, pp.51-61) demonstrate their BIM-based LCA approach for the detailed design stage of a commercial building in Australia. Antón & Díaz (2014, p.1347) perform a *SWOT* analysis for the integration of BIM and LCA in the early design stages and show the demand for design-integrated approaches. Basbagill et al. (2013, p.82) provide a literature review on BIM-based LCA. Furthermore, they present their own approach, combining various specialized software, including the BIM software *DProfiler*, *eQuest* for energy simulation, *SimaPro*, and *Athena EcoCalculator* for LCA. Similar approaches combining multiple software packages can be found in other studies; Aurélio et al. (2011, p.7) use *TRNSYS*, *SketchUp* and *OpenLCA*. These setups deliver detailed results, but expert knowledge is needed to operate such a complex chain of software. Therefore, it is not applicable in architectural practice.

Some academic approaches employ BIM and a combination of analysis software packages for optimization based on LCA. Flager et al. (2012, pp.197-199), for example, perform a cradle-to-gate analysis to optimize the building envelope for minimum life cycle costs (LCC) and minimum Global Warming Potential. Ostermeyer et al. (2013, p.1772) also optimize for minimum LCA and LCC results and provide a Pareto-front for one case study. The computation time needed for this detailed assessment using a chain of different software packages is very high and results in too much effort for practical application. Furthermore, the case studies focus on the optimization of material choices and do not include the parametric variation of the geometry.

In general, parametric approaches to the LCA of buildings are rare. The most advanced study currently found in the literature by Heeren et al. (2015, pp.9832-9841) describes a detailed parametric model for joint assessment of operational and embodied environmental impact. A great number of parameters can be varied, but only a few parameters describe the geometry, such as the building size and the size of windows. A link to CAD is missing, making the approach valuable for research purposes, but impractical for application in the architectural design process.

In the field of product design, Ostad-Ahmad-Ghorabi published a dissertation on the integration of LCA into design using CAD and introduced the term *'parametric Ecodesign'* (Ostad-Ahmad-Ghorabi 2010). His method is employed for a case study of the design for a crane (Ostad-Ahmad-Ghorabi & Collado-Ruiz 2011, p.394), but the parameters that are varied are very limited and do not include variation of the geometry. While there are some parametric approaches to integrate the analysis of the operational energy demand into design as shown in the next part, there is no adequate parametric approach to integrate LCA into the architectural design process.

1.4.2.3. Energy demand calculation in the design process

The most fundamental decisions, such as the building form, orientation, and window layout are often made by architects in the early design stages, with little or no support from simulation software (Picco et al. 2014, p.498). Weytjens et al. (2009, p.293) report that only 20% of architects employ simulation and analysis software as design support tools. In recent years, various incentives have been initiated to shift performance analysis of buildings from the detailed design stage to the early design stages, such as *IPD* as described in Section 1.3.3. The performance of a building design can be analysed according to various criteria, such as daylight availability, energy demand, spatial accessibility, and visual field analysis.

As described in Section 1.2.2.2 , there are two possibilities for determining the building's operational energy demand: *dynamic building performance simulation* (DBPS) and *quasi-steady state methods* (QSSM). Most scientific approaches to integrate energy analysis into the architectural design process propose the application of DBPS, e.g. Morbitzer et al. (2001, p.698), Petersen & Svendsen (2010, p.1114), Negendahl (2015, p.41). DBPS tools allow for modelling of complex systems and their interrelationships. They achieve a high level of detail and can calculate energy demand precisely. According to Morbitzer et al. (2001, p.697) they have not yet been recognized as design support tools to the same extent as design software. There are a number of obstacles to the application of DBPS within the design process, especially in the early stages of design. First of all, a large number of boundary conditions need to be defined, but only limited information is available about the building in the early design stages. Second, input of these boundary conditions requires extensive background knowledge, making it difficult for non-experts to apply DBPS. Third, the simulation is computationally intensive. Depending on the size of the building, the simulation can take between 20 seconds and 5 minutes on a standard PC. While this may be acceptable for a single simulation, the time required for simulating many variants, as required for optimization, quickly multiplies to many hours or even several days – clearly too long for the early design stages. Finally, the time and effort required for DBPS and the resulting additional costs often exceed the budget for common residential buildings.

In comparison with DBPS, QSSM consists of simple algorithms. These can be easier understood by the user, giving a higher degree of transparency. Due to the simple algorithms, the results can be quickly calculated and given out in real time. As such, QSSM is a powerful tool for the early design stages. However, certain dynamic effects are neglected and complex situations therefore cannot be modelled precisely. Nevertheless, Carlos & Nepomuceno (2012, p.206) show that QSSM can produce valid results for moderate climates. According to van Dijk et al. (2006, p.262), the monthly balancing of QSSM is well suited for continuously heated buildings in warm, moderate, and cold European climates. Therefore, it is adequate for residential buildings, which are mostly continuously heated.

For both methods, DBPS and QSSM, commercial tools for design-integration exist. These are divided into CAD/BIM-based tools and parametric tools.

Each of the major BIM software companies has a proprietary integrated-energy-demand calculation, e.g. *Autodesk Green Building Studio*[51] or *Graphisoft EcoDesignerSTAR*[52]. A simplified means of inputting the geometry is realized with the 3D CAD program *SketchUp*[53]. The user simply draws a thermal model consisting of 2D surfaces forming the building envelope. A plug-in transfers the geometry information to a DBPS program, e.g. *OpenStudio*[54] to *EnergyPlus* or *IES plug-in*[55] to *IES VE*[56]. In addition to these plug-ins, there are stand-alone tools with their own 3D geometry modellers, e.g. *Design Builder*[57]. Weytjens et al. (2011, p.243) analysed six common tools for energy demand calculation and concluded that no tool is entirely adequate for architectural use.

A variety of interfaces to DBPS exist for parametric design tools. A connection to *EnergyPlus* is provided by the plug-ins *Archsim*[58], *Honeybee* (Roudsari et al. 2013, pp.3128–3130), and *Diva* (Jakubiec & Reinhart 2011, pp.2202–2206). *Archsim* and *TRNSYS-Lizard* (Frenzel & Hiller

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[51] Green Building Studio is a cloud-based energy analysis software for Autodesk Revit http://www.autodesk.com/products/green-building-studio/overview (accessed March 12th 2016)

[52] Graphisoft EcoDesigner STAR is an energy analysis extension for Archicad http://www.graphisoft.com/archicad/ecodesigner_star/(accessed March 12th 2016)

[53] SketchUp is an intuitive 3D CAD programme by Trimble available for free at https://www.sketchup.com/download (accessed February 22nd 2016)

[54] OpenStudio is an open source software provided by the National Laboratory of the U.S. Department of Energy and can be downloaded at https://www.openstudio.net/ (accessed March 12th 2016)

[55] IES plugin is a plugin for SketchUp to translate models to IES VE, https://www.iesve.com/software/interoperability/sketchup (accessed March 12th 2016)

[56] IES VE is a whole building simulation software, see https://www.iesve.com/software/ve-for-architects (accessed March 12th 2016)

[57] Design Builder is a modular software comprising of 3D modelling tools and energy and daylighting analysis modules, http://www.designbuilder.co.uk/ (accessed March 12th 2016)

[58] ArchSim is a plug-in to link EnergyPlus with Grasshopper3D. It is developed by Timur Dogan and can be downloaded from http://archsim.com/downloads/ (accessed February 9th 2016)

2014, pp.491–493) also provide an interface for *TRNSYS*. The only parametric plug-in for QSSM described in the literature is based on ISO 13790:2008 and uses an Excel-based balancing software called *Energy Performance Calculator* (Ahuja et al. 2015, pp.3–6). This requires importing and exporting data, which increases the complexity of the workflow. Therefore, a new, fully integrated plug-in based on DIN V 18599-2:2011 was developed for this thesis. The development is described in Lichtenheld et al. (2015, pp.1-3).

1.4.3. Time-efficiency of existing approaches

In general, efficiency can be described as a ratio between output and input. In the case of the time-efficiency of optimization methods, the input equals the time for the optimization procedure and the output equals the improvement achieved through the optimization. As such, the time-efficiency of an environmental design optimization method can be defined as the ratio between the reduction in environmental impact and the time needed for the application of the method. To measure time-efficiency, both the reduction in impact through application of the method and the time needed for its application have to be measured.

To evaluate the time-efficiency of existing approaches, only the commercial tools were assessed, because no description of the time needed to carry out an LCA using any of the academic approaches can be found in the literature. As already noted, the currently available commercial approaches do not offer the opportunity for design optimization. Therefore, the reduction in impact achieved through the optimization process cannot be measured. Thus, the focus is on the time needed for calculation of the LCA.

Comparing the time needed to carry out an LCA using different approaches is difficult. On the one hand, the time needed for application of the method depends on the method itself; on the other hand, it also depends on various boundary conditions, including user-related parameters, such as the experience of the user or the performance of the computer employed. The distinction between these parameters made here is shown in Table 19.

Table 19: Parameters affecting time-efficiency of methods for environmental building design optimization methods based on LCA

Parameters of the method	Boundary conditions
Approach for geometry input	Graphical user interface
Predefined data	Experience of user
Simplifications	Performance of computer
Algorithms used for calculation	Efficiency of computational optimizer employed
Optimization approach	Size and type of the building

To get a rough overview of the times needed, four students were each provided with one of four commercial tools representing each category[59]. They were asked to carry out an LCA of the same five storey residential building and provided with existing documentation from a study by Hartwig (2012), which included all of the necessary information. As such, the students did not have to acquire the information themselves. The necessary steps included input of known parameters, calculation, and output of the LCA results. As noted in Section 1.3.4, the optimization step consists of adjustment of input parameters, re-calculation and outputting the results again. As such, one optimization loop equals the calculation of one variant. Therefore, in addition to calculating the LCA of the original building, the students were also asked to calculate a variant with some modified building materials. The times that they needed (without an initial introduction to the software) are shown in Table 20.

Table 20: Time students needed for LCA of a residential building using different tools

Type	Tool	Time for first variant	Time for second variant
Generic	GaBi	2 days	3 hours
Spreadsheet-based	Legep	6 days	9 hours
Component catalogue	eLCA	3 days	5 hours
BIM-based	Tally	3 days	5 hours

These times cannot be regarded as representative, however they clearly indicate that the first LCA takes much longer, and that a change in building materials can be carried out with less additional effort. Nevertheless, the time needed for a second variant amounted to at least 3 hours.

In the literature, the only values for the time needed for the LCA of buildings were found in a white paper published by Bionova (Pasanen 2015). According to Pasanen (2015, p.1), the data are based on recorded time spent in 31 different real-life cases with different users, projects, and software tools (see Table 21).

[59] The students Anna Krtschil, Markus Engelmann, David Kruppke, and Katharina Elert carried out the LCA as part of their bachelor thesis at Bauhaus University Weimar in 2015.

Table 21: Time needed for LCA using different approaches according to Pasanen (2015, p.1)

Approach	Software tools	Time
Classical process	Various	30-110 hours
LCA made easy	360optimi	4-11 hours
State of the art (BIM)	One Click LCA	1 hour

The one hour recorded for *One Click LCA* does not include building the BIM, instead it reflects the time required to perform an LCA using a completed BIM. If the time needed to build the BIM is accounted for, it would probably be comparable to the 3 days the student needed for the LCA using Tally (see Table 20).

1.4.4. Research gap

The analysis of the current approaches for LCA of buildings in research and in practice leads to the conclusion that there are two main types of approaches: very complex, high-end solutions and over-simplified tools.

Complex solutions include generic LCA tools, Legep, BIM-based tools, and the academic approaches evaluated. They provide a high level of detail, but require a lot of information that is usually only available in later design stages. Expert knowledge is needed to correctly operate the tools and the analysis is laborious. Legep, BIM-integrated, and the evaluated academic approaches consider all life cycle modules and some additionally provide the option to evaluate life cycle costs. As such, they allow for a holistic assessment of the building design. However, the effort required to apply these tools results in high costs, which might be acceptable for large, high-end building projects, but not for common residential buildings. Residential buildings account for 75% of the floor area in Europe (Economidou et al. 2011, p.30), which clearly indicates the demand for simplified methods.

Over-simplified tools, such as online component catalogues or simple spreadsheet-based tools, usually only consider the embodied impact of the building's life cycle. In consequence, only sub-optima are found, and the broader picture can be missed. The same is true for common energy demand tools (DBPS and QSSM), which only consider the operational energy demand. While initial input of information to these tools is simple, changes in the design or comparison of variants is labour-intensive, as the input for each variant must be manually adjusted.

Figure 21 plots available LCA tools for buildings with respect to their complexity and their holism. It can be seen that they are either very complex and holistic or simple but not holistic. There is no tool simple enough for application in the architectural design process which provides a holistic evaluation of the building. The higher the complexity, the higher the effort and the time needed for application.

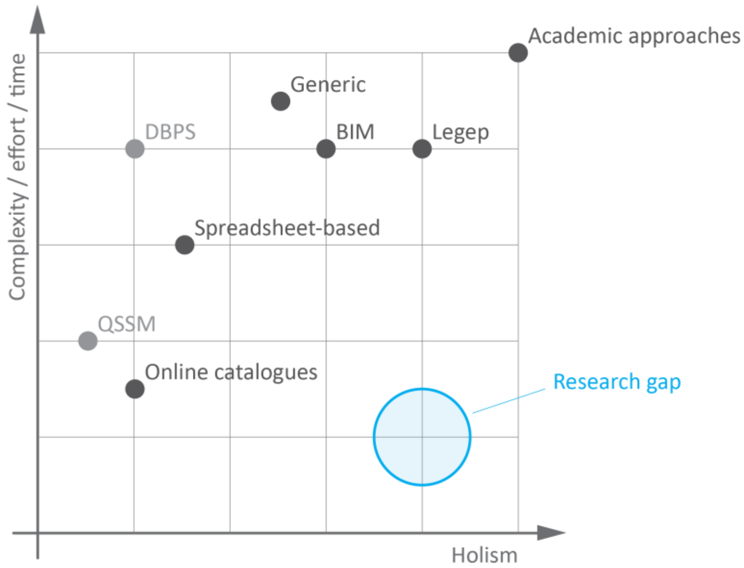

Figure 21: Gap in current tools

All current approaches lack the ability to efficiently optimize the design. As noted earlier, this is the greatest issue, because without optimization, the LCA does not have any real significance, since the environmental impact of the building is not reduced.

This research gap is the basis for the development of requirements for environmental building design optimization methods.

1.4.5. Summary of Section 1.4

What are the challenges to integrating LCA into the design process?

Numerous challenges arise when undertaking LCA during the design process. The main challenge is that LCA results have the greatest influence when carried out in stage 2, but the necessary information is only available after stage 4, when LCA results are impractical to implement. Furthermore, most buildings are unique designs. This makes every kind of optimization difficult, because only a limited effort can be spent on optimization compared with a serially produced product. The numerous design parameters, such as geometry, building materials, and building services influence each other. Deadlines in the design process are usually very short. Therefore, the optimization results must be provided quickly, making very time-efficient optimization methods necessary.

What are the characteristics of common LCA approaches for buildings, and which opportunities for design optimization do they provide?

An evaluation of existing commercial tools indicates that none of the currently available commercial approaches is suitable for application in the architectural design process. None of the tools allows for optimization of the building's environmental impact. Most tools only calculate the embodied impact, and require external calculation of the operational energy demand, which can lead to sub-optimal solutions. Academic approaches to integrate LCA in the architectural design process allow for optimization, but employ a complex chain of software, and are therefore not applicable in practice. In general, parametric approaches for the LCA of buildings are rare.

Most scientific approaches to integrating energy analysis into the architectural design process use dynamic building performance simulation (DBPS). They achieve a high level of detail, but require extensive background knowledge. Quasi steady state methods (QSSM) use simple algorithms and can quickly output results, making them a powerful tool for early design stages. For both methods, DBPS and QSSM, commercial plug-ins for CAD/BIM-based tools and parametric tools exist. These tools do not consider embodied environmental impact and therefore do not provide the potential for holistic optimization.

How time-efficient are existing approaches?

To evaluate the time needed for LCA using existing approaches, four students were provided with one tool from each category. In all cases, the calculation of the LCA for a first variant took at least 2 days, and a second variant at least 3 hours. In the literature, no specification of the time needed to carry out an LCA using any of the academic approaches could be found. Therefore, the time needed for these approaches could not be evaluated.

Which research gap can be identified?

The analysis of current approaches for the LCA of buildings in research and in practice leads to the conclusion that they are either very complex but holistic or simple but not holistic. There is no adequate tool for application in the architectural design process. Furthermore, all current approaches lack the opportunity to time-efficiently optimize the design. This is the greatest issue, because without optimization, the LCA results do not have any real significance, since the environmental impact of the building is not reduced.

1.5. Summary of Chapter 1

What are the main characteristics of LCA and the architectural design process as they pertain to the environmental optimization of buildings, and where is the research gap?

An analysis of currently available methods for environmental system analysis indicates that LCA is most suitable for the evaluation of environmental sustainability of buildings. LCA analyses inputs, outputs, and environmental impact throughout the whole life cycle. Regulations for the application of LCA for buildings exist, and environmental data is becoming increasingly available, for example in the form of databanks or environmental product declarations (EPDs).

The architectural design process usually consists of six main stages. Decisions made in the early stages of the design process, namely stages 1 and 2, have the greatest influence on environmental impacts. As such, design optimization is best achieved in these stages. The dilemma of LCA during the design process is that decisions taken in stage 2 have the greatest influence, but the information available is scarce and uncertain. Information needed for a complete LCA is only available after stage 4. By then the LCA results are less useful, because making significant changes at this stage is too costly. Basically, once the necessary information is available, the LCA results are impractical to implement.

The challenges for the integration of LCA in the design process include short deadlines in the design process, the uniqueness of buildings, and the lack of practical tools, amongst others. Numerous tools for LCA and energy analysis for buildings exist, however the analysis indicates that these are either very complex but holistic or simple but not holistic. Furthermore, none of them provide the opportunity for optimization in the architectural design process, which is the main research gap.

2. Requirements for environmental building design optimization methods based on LCA

The research gap described in Section 1.4.4 indicates the current lack of a method for environmental building design optimization applicable to the architectural design process. Therefore, a novel parametric method has been developed in this thesis (see Chapter 3). A requirement catalogue developed to confirm that the method meets the requirements for application in the design process is described in this chapter. This requirement catalogue can serve both to provide a guideline for the development of new methods for environmental building design optimization based on LCA and to evaluate existing methods.

To structure the requirements, the typical workflow described in Section 1.3.4 is used, and the requirements are defined separately for the four steps, namely input, calculation, output, and optimization in parts one to four of this chapter. The requirement of time-efficiency is important in all four steps. It is most important for optimization, because many variants have to be compared in the optimization process (see Section 1.3.4). As such, a small increase in the time needed for one of the first three steps (input, calculation, or output) can quickly amount to a great increase in the time necessary for optimization. Therefore, this requirement is discussed in the fourth part.

Within each step, a distinction between mandatory requirements and optional recommendations is made. The mandatory requirements mainly serve to guarantee a minimum level of quality for the LCA results and a minimum level of applicability. To evaluate whether this minimum quality has been met, the requirements contain yes-no questions. If one of the mandatory requirements cannot be fulfilled, the method cannot be regarded as adequate for environmental optimization in the architectural design process. Optional recommendations aim to further improve the applicability. Most of these recommendations are qualitative criteria which could only be quantified by a large survey of architects. This is beyond the scope of this thesis, and therefore the recommendations are reduced to yes-no questions.

The following requirements are structured into a description which includes literature sources, a yes-no question, and a description of the form of documentation necessary to prove to that the requirement has been met. The classification of screening, simplified, and complete LCA (see Section 1.2.2.5) is incorporated in the requirements, but only the screening and simplified LCA are covered in detail, because they are the most relevant for application to the design process. To facilitate the evaluation of environmental building design optimization methods using the established requirements, a checklist is provided in the summary of this chapter. In Chapter 4, this checklist will also serve to evaluate the parametric method developed in Chapter 3.

2.1. Requirements regarding input

The mandatory input requirements mainly focus on the system boundaries, assumptions for simplification, and the data quality. They include the following:

- Life cycle modules
- Environmental indicators
- Environmental data quality
- Minimum building components to be included in the 3D geometric model
- Reference study period

An optional requirement is provided for predefined values. Each requirement is discussed in detail in the following.

2.1.1. Life cycle modules

Description: The main point of simplification in LCA is determining the system boundaries. The system boundaries for the LCA of buildings are defined by the choice of life cycle modules. To provide transparency in the LCA results, the included life cycle modules have to be declared. For screening LCA, the mandatory modules A1-A3 and B6 defined by EebGuide (Wittstock et al. 2012, pp.49-51) are prescribed (see Table 22). In contrast to EeBGuide, module B7 is neglected, because the water demand is not directly influenced by the building design. For simplified LCA, the life cycle modules as defined by DGNB and BNB building certification systems are employed. This means that the life cycle modules A1-A3, B4, B6, C3-C4 and D must be included (see Table 22).

Table 22: Life cycle stages to be considered (based on EN 15978:2012 p. 21)

Product			Construc-tion		Use Stage							End of Life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply**	Transport**	Manufacturing**	Transport	Construction	Use	Maintenance	Repair	Replacement*	Refurbishment	Operational energy use**	Operational water use	Demolition	Transport	Waste processing*	Disposal*	Re-use recovery and recycling potential

* Mandatory for simplified LCA
** Mandatory for screening and simplified LCA

In addition to following the recommendations of EeBGuide, DGNB, and BNB, the following justifications for life cycle module choices are provided:

- Typically, the product stage (modules A1-A3) of a material has the largest share of the embodied impact, and must therefore be included. As described in Section 1.2.2.1, data for these modules are declared with a high certainty in all EPDs and all databanks for building materials. As such, they can be included without difficulties.
- As described in Section 1.2.2.1, the module A4 depends on the distance between the construction site and the manufacturer's plant. In the early design stage, the location of the factory is usually unknown. Furthermore, Kellenberger & Althaus (2009 pp.823-825) show that the influence of the transportation is not very high (see Section 1.2.2.1).
- Data on the construction process (A5) is very rare, and this module is therefore neglected. According to John (2012, p.147), preparatory works on the building site are negligible.
- The use stage contains seven modules which are described in Section 1.2.2.1, but only B4 and B6 are included and the modules B1, B2, B3 and B5 are neglected, because data is very rarely available.
- As described in Section 1.2.2.1, data for modules C1 and C2 is usually not available and these modules are therefore neglected.
- Because of the difficulties that module D introduces (see Section 1.2.2.1), its integration is regarded as optional. Nevertheless, its inclusion is recommended, both in order to be in line with DGNB and BNB, and to provide a holistic picture, including the recycling potential of materials.

Yes-no question:	a) Screening LCA: Are the life cycle modules A1-A3, and B6 included? b) Simplified LCA: Are the life cycle modules A1-A3, B4, B6, C3, C4, and D included?
Documentation:	Declaration of included life cycle modules in the description of the method.

2.1.2. Environmental indicators

Description: Some LCA studies of buildings only consider one or a few environmental indicators, usually primary energy, e.g. Fay et al. (2000), or global warming potential (GWP), e.g. Çomaklı & Yüksel (2004). Using only one indicator may be adequate for a specific study, however, for holistic optimization of building designs this is impractical, as it might lead to sub-optimal solutions. Most wood-based products have a negative GWP, for example. As such, only considering GWP in the design process would lead to the conclusion that the more wood is used, the better the environmental performance, which clearly is not the case when taking other indicators into account as well. As noted in Section 1.2.1.5, the impact categories do not cover all relevant environmental aspects, and there is no data available for building materials for all currently known environmental problem fields. Nevertheless, the intent should be to cover a wide range of environmental aspects. Currently, there is no European agreement on which indicators are most relevant for the building sector, and national regulations differ from each other. The Swiss standard for embodied energy only demands the declaration of PENRT and recommends the assessment of GWP optionally (SIA 2032:2012, p.16). The Swiss KBOB database additionally declares *eco points* (UBP). In Austria, three indicators, namely PENRT, GWP, and AP, are aggregated into one *OI3* index (IBO 2016, p.6). EeBGuide recommends the use of three indicators (PET, PENRT, and GWP) for screening LCA and other indicators if relevant (Wittstock et al. 2012, p.33).

Here, a distinction is made between mandatory indicators for screening and simplified LCA: for screening LCA, at least three indicators covering different environmental problem fields are required. The choice of PENRT, GWP, and AP fulfils this requirement, for example, but PET, PERT, and PENRT do not, as they only cover the use of energy. For simplified LCA, the DGNB and BNB guidelines are followed and inclusion of at least the following list of indicators in the environmental data input is considered mandatory:

- Primary energy total (PET)
- Primary energy non-renewable total (PENRT)
- Global warming potential for a time horizon of 100 years (GWP)
- Eutrophication potential (EP)
- Acidification potential (AP)
- Ozone layer depletion potential (ODP)
- Photochemical ozone creation potential (POCP)

Yes-no question: Screening LCA: Are three indicators included which cover different environmental problem fields?
Simplified LCA: Are PET, PENRT, GWP, EP, AP, ODP, and POCP included?

Documentation: Declaration of environmental datasets employed and output of the respective indicators.

2.1.3. Environmental data quality

Description: Environmental data is only valid for a certain time period and a specific geographic context. Some databanks include datasets out of time (see Section 1.2.2.4), and environmental data is only valid for a certain region or nation. The electricity mix used for production can vary greatly between different nations, for example between Germany and Austria. To make sure the environmental data is valid, the employed datasets have to be declared. In the early design stages, it is difficult to know the origin of the materials. As such, employing data for the specific geographic region can only be recommended, but not required. Furthermore, as far as possible, data should be employed from a single database to ensure that environmental data for different components are based on similar assumptions (Wittstock et al. 2012, p.190).

As described in Section 1.2.2.4, environmental data on building materials can be categorized as specific, average, or generic. Specific data is the most accurate, however the manufacturer is usually not known in the early design stages. Therefore, the application of average data or generic data is recommended for screening LCA, and specific data is recommended for simplified LCA. This is in line with the recommendations of EN 15978:2012 (p.39).

Yes-no question: Is the environmental data valid?

Documentation: Declaration of environmental datasets employed and the year of the LCA study.

2.1.4. Minimum building components to be included in the 3D model

Description: A bill of quantities (BOQ) of all building materials is necessary for the LCA calculation. To establish this BOQ, the volumes of all components have to be known. Manually calculating the BOQ is laborious and error-prone. Therefore, an automatic take-off of the quantities based on a 3D model is needed. Furthermore, most architects are mainly visually oriented in their work (Meex et al. 2016, p.1314), and according to a survey by Weytjens et al. (2009, p.293), 70% (increasing tendency) of 319 architects interviewed employ simple 3D models in the design process. For these reasons, the input of the geometry using a 3D model is a mandatory requirement.

3D models show great differences in the level of detail. In order to allow for easy modification in early design stages, the model should be as simple as possible, but still allow for automatic quantity take-off. The required level of detail corresponds to the *level of development 200* (LOD 200) defined by NATSPEC (2013, p.10) for BIM, which is recommended for BIM use in Germany in design stages 2 and 3 (Egger et al. 2013, p.59). This means that the model consists of generalized components. Windows, for example, are indicated by their size, position, and orientation, but not modelled precisely (NATSPEC 2013, p.5).

The accuracy of the BOQ should match the design stage and the level of complexity of the LCA. Therefore, the minimum building components are defined separately for screening and simplified LCA. Guidelines, such as EeBGuide, do not specify the accuracy of results using screening or simplified LCA. In the literature, few studies compare the deviation between different levels of LCA. A comparison between simplified and complete LCA for a building by Bonnet et al. (2014, p.276) shows a maximum deviation of 20%. Another LCA study for a building by Lasvaux & Gantner (2013, p.414) shows a deviation of 30% in GWP between simplified and complete LCA. A study of different methods for screening LCA of cell phones and vacuum cleaners shows deviations up to 60% when compared with a complete LCA (Hur et al. 2005, p.232). To specify a maximum allowed deviation, the variation in the level of detail for cost estimation in Germany is considered, because it is also based on a BOQ and shows many similarities. The German fee structure for architects and engineers (HOIA) defines the level of detail in the cost estimation according to the design stage. The generally accepted deviation between the estimated and the final costs is 30% in design stage 2, and 20% in design stages 3 and 4 (Liebchen 2013, p.150). These values serve as a guideline when determining the maximum acceptable deviation for screening and simplified LCA.

For screening LCA, the main building components to be considered should include at least the building envelope, including exterior walls, windows, roof and floor slab, and the primary load-bearing structure, because they are cumulatively responsible for approximately 76% of the embodied impact on average (El Khouli et al. 2014, p.48). As such, the neglected components amount to a deviation of approximately 24%, which is less than the recommended 30% maximum.

For simplified LCA, the components listed as mandatory in the DGNB and BNB simplified approach (see Section 1.2.2.5) should be included, in order to be in line with these certification systems. This includes foundations, interior walls, building services, and surface finishings, in addition to the components listed previously. It is assumed that the deviation is then lower than the recommended 20% maximum. The building components to be included are listed for both types of LCA in Table 23.

Table 23: Building components to be included in the 3D model for LCA

Screening LCA	Simplified LCA
Exterior walls Windows Roofs Ceilings Slabs Load bearing interior walls Columns	Exterior walls Windows Roofs Ceilings (including finishing) Slabs (including finishing) Load bearing interior walls (including finishing) Columns (including finishing) Foundations Non-load bearing interior walls (including finishing) Interior doors Building services

In addition to these building components, there are components which usually have a marginal influence on the mass of the building, such as cables and sealants, but can have a relatively great influence on certain indicators, e.g. ADPe (Eberl et al. 2014, p.169). However, modelling these components is labour intensive. Especially in the early design stages, the amount of cable or the number of joints and seals, for example, is unknown. Furthermore, data availability on a wide range of these materials is not complete. For example, ökobau.dat only lists some individual materials, and the variety of products makes the application of EPDs difficult. Therefore, these components are excluded here.

Yes-no question: a) Screening LCA: Are the building envelope and the primary load-bearing structure included?
b) Simplified LCA: Are exterior walls, windows, roofs, ceilings, slabs, foundations, interior walls, columns, and building services included?

Documentation: A screenshot of the 3D geometry model used for input and a description of the components included.

2.1.5. Reference study period

Description: EN 15978:2012 does not provide a predefined reference study period (RSP), and the RSPs in European studies and certification systems differ. DGNB and BNB, for example, use 50 years, whereas Swiss *Minergie-Eco* label uses 60 years (Minergie 2016, p.1), and Austrian *Eco2soft*[60] online calculator uses 100 years as the default RSP. EeBGuide proposes

[60] Eco2soft is an online software tool for embodied impact calculation of buildings available at https://www.baubook.info/eco2soft/ (accessed March 12th 2016)

an RSP of 50 years as a baseline scenario for comparison purposes (Wittstock et al. 2012, p.94). In the case of a refurbishment, e.g. the application of external insulation as part of an operational energy saving measure, it might be more realistic to employ 30 years. Here, the default is set to 50 years, but considering other RSPs is recommended if they seem to be more realistic. Therefore, declaring the RSP assumed for the analysis is mandatory, and it is recommended that the method provides the possibility to adjust the RSP.

Yes-no question: Is the assumed RSP of the building declared?

Additional question: Can the RSP be adjusted for different scenarios?

Documentation: Declaration of the assumed RSP and an optional description of how it can be adjusted.

2.1.6. Predefined values

Description: According to Schneider (2011, p.39), the influence on the building's environmental impact is greatest in early design stages. As such, those stages have the greatest potential for optimization (see Section 1.3.1). According to El Khouli et al. (2014, p.73), LCA should be employed as early as possible to evaluate different variants in the early design stages and to use the results to make the best decisions. Environmental building design optimization methods should therefore be applicable in the early design stages. However, in those stages, the information required for LCA might be missing, as described in Section 1.3.1. In most cases, the rough geometry is defined in stage 2 of the design process, while the material is defined in detail in stage 3 or 4. Therefore, the process should to be structured in such a way that analysis can proceed without the missing information and make adequate assumptions to fill in the gaps. This can be realized by providing predefined data for all necessary input variables related to building materials and building services. Furthermore, according to Meex et al. (2016, p.1313), predefined values are one important criterion for the user-friendliness of LCA tools for buildings.

Ideally, the choice of predefined values should be based on the most common building materials and services for the specific building type and region of the building site. For example, if 80% of the ceilings in single-family houses in Germany are made of reinforced concrete, 15% made of wood, and 5% made of steel beams with a concrete slab, an average value can be determined. König et al. (2010, pp.21–51) use this approach to generate average values for whole buildings, however, they do not declare values for individual components. Values for Switzerland can be found in SIA 2032:2010 (pp.23-24), for example, but only for the indicators PENRT and GWP. To generate average values for all European regions an extensive study would be required, because this data is currently not available. At the moment, default values on typical materials can only be an optional recommendation for future development. Architects can only assume a realistic material or building service based on their knowledge. For example, if ceilings in Germany are mostly made of reinforced concrete, they can choose concrete as the default material. To make the choices transparent to decision-makers, the assumptions have to be declared and explained.

In order to replace these values once detailed information is available in later design stages, the method should be flexible. Furthermore, the method should allow for easy modification of input parameters – including building materials, building services, and the geometry. As explained in Section 1.3.3, some changes to the design are not in the hand of the architect and cannot be anticipated. Therefore, the method should allow for changes throughout all design stages. To evaluate the flexibility, the amount of time needed for changes can be measured. This time is also evaluated in the requirement *time-efficiency* described in Section 2.4.2 and therefore not included in the requirements for input, despite being an important aspect.

Yes-no question:	Are predefined data based on the most typical building components provided?
Documentation:	Declaration of the predefined values.

2.1.7. Summary of Section 2.1

Which requirements are necessary for the data input?

The requirements for input are listed in the following with an indication as to whether a requirement is mandatory (M) or optional (O):

- **Life cycle modules (M):** For screening LCA, the life cycle modules A1-A3 and B6 must be included. For simplified LCA, the modules A1-A3, B4, B6, C3, C4 and D must be included and declared in the documentation.
- **Environmental indicators (M):** Three indicators which cover different environmental problem fields must be included for screening LCA. For simplified LCA, the indicators required by the DGNB building certification system, namely PET, PENRT, GWP, EP, AP, ODP, and POCP, must be included. The environmental datasets employed have to be declared in the documentation and the respective indicators output.
- **Environmental data quality (M):** The environmental data employed must be valid and should be suitable for the region relevant to the building site. This is documented by declaring the environmental datasets employed.
- **Minimum building components to be included in the 3D geometry model (M):** For screening LCA, the building envelope and the primary load-bearing structure must be included. For simplified LCA, the following components must be included: exteri-

or walls, windows, roofs, ceilings, slabs, foundations, interior walls, columns, and building services. A screenshot of the 3D model and a description of the components should be included for documentation.

- **Reference study period (M/O):** Declaring the assumed RSP in the documentation is mandatory. The reference study period (RSP) should be adjustable for different scenarios, which is optional. The description of the method should include an explanation of how to change the RSP.
- **Predefined values (O):** To facilitate the application of the method, especially in the early design stages, predefined data should be provided which are based on typical building components in the region where the building site is located. The assumptions for the predefined values should be described in the documentation.

2.2. Requirements regarding calculation

Calculation algorithms form the core of every building performance analysis method. Here, the calculation includes all necessary steps to conduct the LCA, including establishing a BOQ based on the geometry and material input, the multiplication by environmental impact factors, calculation of the number of replacements, and calculation of the operational energy demand, amongst others. There are two mandatory requirements for calculation algorithms for LCA of buildings:

- Combined calculation of embodied and operational impact
- Operational energy demand calculation

2.2.1. Combined calculation of embodied and operational impact

Besides the differentiation of life cycle modules according to the life cycle stages (see Figure 12), a distinction can also be made between the methods of calculating the impact resulting from the modules. To calculate the environmental impact resulting from the operational energy use of the building (module B6), an energy demand calculation is necessary. In this thesis, this kind of impact is called an *operational impact* (I_O). The modules for production, replacement, and EOL of the building materials (A1-A3, B4, C3, C4, and D) are basically calculated by multiplying the BOQ by environmental impact factors (the detailed calculation is described in Section 3.1.2). These modules are combined in the *embodied impact* (I_E).

In order to guarantee that the environmental building design optimization is effective and meaningful, the most important requirement is that the assessment of the building design is holistic (Finch 1994, p.1437). This means that, in addition to guaranteeing a minimum level of detail within each aspect, both aspects I_O and I_E must be assessed together. As Table 18 shows, most commercial tools for LCA only calculate I_E and require external calculation of the operational energy demand needed for I_O. Tools for energy demand calculation do not consider I_E. Besides the additional effort that the external calculation involves, it can lead to sub-optimal solutions, because the building design can only be optimized for one criterion – either I_O or I_E. In order to avoid problem shifting from one life cycle module to another, I_O and I_E - namely life cycle modules A1-A3, B4, B6, C3, C4, and D - must be assessed together. To prove that the method carries out all necessary calculations within one calculation step and no external calculation and importing of results is needed, the calculation algorithms have to be described briefly. This makes the calculation process transparent to the user.

Yes-no question:	Are the modules of I_E (A1-A3, B4, C3, C4 and D) and of I_O (module B6) linked and calculated together?
Documentation:	Description of the calculation algorithms.

2.2.2. Operational energy demand calculation

Description: As described in Section 1.2.2.2, the calculation of the operational energy demand is the basis for calculating the impact from life cycle module B6. It has a large influence on the environmental impact of the building, which makes it necessary to define a minimum standard for the accuracy of calculation. While the other requirements are meaningful for all types of buildings in industrialized countries, the level of detail for operational energy demand calculation is specifically defined for residential and office buildings in Western Europe. For other types of buildings or other climatic regions, other types of energy demand might be relevant. As shown in Section 1.2.2.2, the architect can influence building-related operations, and thus these must be considered. In contrast, user-related operations can be neglected, as the architect has little influence over them through the design of the building. In addition, Szalay & Zöld (2007, p.1761) argue that evaluating building-related and user-related operations together might result in the energy performance of the building becoming 'lost' in the complex calculation. They suggest that low building quality might be compensated through efficient appliances.

Building-related operational energy demand significantly affected by the building design, namely space heating and cooling, is most important for architects. In Western Europe, the environmental impacts resulting from those energy demands are still the most significant in the building's life cycle. Therefore, specific calculation of the operational energy demand for space heating and cooling is regarded as mandatory for both screening and simplified LCA. This is contrary to the recommendations of EeBGuide (Wittstock et al. 2012, p.50), which proposes to use anticipated energy performance targets for the energy demand in the use phase for a screening LCA, and only calculate the energy demand for simplified and complete LCA. As shown in Section 1.2.2.2, different methods with different levels of detail exist for energy demand calculation. The main difference is the time step in which the energy balance is established. To guarantee a minimum level of detail here, it is required that monthly time steps (or smaller) are used for the calculation of the operational energy demand for space heating and cooling.

The final energy demand is necessary for the LCA calculation. In the early design stages, the exact configuration of the building services is usually not known, and they cannot be modelled in detail. As such, the exact losses within the building cannot be calculated. Therefore, a simplified approach can be employed to calculate the final energy demand (cf. DIN V 4701-10:2003 and DIN V 4701-10:2007 Beiblatt 1). The final energy is calculated by multiplying the useful energy resulting from the energy balance by a global factor describing the annual efficiency of the building service.

The architects' influence on energy demand is limited for building-related operations primarily dependent on the building services, e.g. electricity for lighting. Nevertheless, it can be useful to assess this design-unaffected energy demand to provide a relation for the optimization potential of design-affected energy demands in the context of the whole building. Therefore, this type of energy demand can be integrated optionally using statistical values.

The assumptions for the adequate level of detail for operational energy demand calculation are summarized in Table 24.

Table 24: Energy demands to be included in screening and simplified LCA

	Screening LCA	Simplified LCA
Energy demand for space heating	Calculated using at least a monthly level of detail	Calculated using at least a monthly level of detail
Energy demand for space cooling	Calculated using at least a monthly level of detail	Calculated using at least a monthly level of detail
Electricity demand*	Statistical values	Statistical values
Energy demand for hot water*	Statistical values	Statistical values
Water demand	-	-

* Optional

Yes-no question: Is the energy demand for space heating and cooling calculated using at least monthly time steps?

Documentation: Description of the method used for energy calculation, including the time steps.

2.2.3. Summary of Section 2.2

Which requirements are necessary for the LCA calculation?

The requirements for the calculation consist of two mandatory criteria:

- **Combined calculation of embodied and operational impact (M):** It must be ensured that the modules of embodied impact (A1-A3, B4, C3, C4 and D) and operational impact (module B6) are linked and calculated together to allow for holistic optimization. This can be documented by a brief description of the calculation algorithms.
- **Operational energy demand calculation (M):** The energy demand for space heating and cooling must be calculated using at least monthly time steps (or smaller). This can be documented by a describing the method used for energy calculation, including the time steps.

2.3. Requirements regarding output

Requirements regarding the output relate to the user-friendliness and applicability of the method. As they are not essential for the quality of the LCA results, all three requirements are optional:

- Visualization of results
- Single-score indicator
- Information on the uncertainty of data

2.3.1. Visualization of results

Description: To allow architects to carry out an LCA of their design during the design process and generate variants for improvement, a method is needed that is both easy to understand and applicable without extensive knowledge and experience in LCA. In addition to simplification and a focus on the most relevant aspects of the life cycle of buildings, the LCA results should be communicated in a way understandable to non-LCA-experts. Furthermore, the method should indicate aspects with potential for improvement. Since architects typically work heavily in visual media (Meex et al. 2016, p.1314), graphical output is assumed to be best understood. The results from a survey of 28 engineers also indicates that a lack of visualization is a main weakness of current programs in their opinion (Attia et al. 2013, p.121). Attia et al. (2009, p.211) recommend that future building performance analysis tools should provide more visual information. The American Institute of Architects also demands that analysis tools should include a “clear graphic output” (AIA 2012, p.47). There are manifold ways of visualizing results which are not rated here, but the requirement is reduced to providing one kind of graphic output.

Yes-no question: Is a graphic output provided?

Documentation: Screenshot of the graphic output.

2.3.2. Single-score indicator

Description: As shown in Section 1.2.1.3, approaches to aggregate individual midpoint indicators into a single-score indicator have been developed to facilitate the communication of results to non-LCA-experts. These can be valuable to communicate the results to architects and their clients. If the client is interested in obtaining a building certification label, for example, it can be useful to directly output the number of points that can be achieved in LCA-related criteria. Furthermore, Meex et al. (2016, p.1314) recommend providing a single-score indicator for architects to allow easy comparison of the environmental performance of building designs to benchmarks or other projects. However, as noted in

Section 1.2.1.3, the weighting steps necessary for this aggregation are based on value choices, and are not scientifically based (ISO 14040:2009, p.18). Decision-making based on various possibly contradictory midpoint indicators is difficult. Kägi et al. (2015, p.130) report that decision-makers always implicitly or explicitly weight and aggregate the LCA results in order to make a decision on it. They furthermore discuss that it might be better to provide a single score for decision-makers instead of letting them make the weighting on their own[61]. Here, the optional output of results in a single-score indicator is recommended. However, the midpoint results should always be declared additionally in order to be in line with ISO 14040:2009.

Yes-no question: Is a single-score indicator output provided in addition to the midpoint indicators?

Documentation: Output of a single indicator in addition to the midpoint indicators and description of the weighting method.

2.3.3. Information on the uncertainty of data

Description: As shown in Section 1.2.1.5, LCA involves large uncertainties. To communicate these to decision-makers, information on the uncertainty of the LCA results should be provided. In order to output this information, information on the uncertainty of data has to be input in the first place. Hoxha et al. (2014, p.63) use two case studies to show that the influence of material quantity uncertainty has a relatively small influence on the LCA results (an average of a 5%). In contrast, the LCA results are very sensitive to uncertainty in environmental data and RSL data. Therefore, it can be assumed that information on the uncertainty of RSL and environmental data should be included, while uncertainty in the BOQ can be neglected. However, information on the uncertainty of RSL and environmental data is not commonly available. Scientific studies provide individual datasets: uncertainty information for RSL data can be found in Hoxha et al. (2014, p.60) or Ritter (2011, pp.225-234), and environmental data uncertainty indicators in Hoxha (2015, pp.226-232). Uncertainty in environmental data is also integrated in specialized LCI databanks, such as Ecoinvent 3.0 (see Ciroth et al. 2013, p.3). However, in building-LCIA databanks such as ökobau.dat, this kind of

[61] The question whether to employ single-score indicator or not was intensively discussed during the meeting of young LCA researchers *Ökobilanzwerkstatt* of the years 2014 and 2015. In conclusion, the best possibility was seen to report both, a single-score indicator and the midpoint indicators from EN 15978 as required by ISO 14040:2009. The report of Kägi et al. (2015) on the Session *"Midpoint, endpoint or single score for decision-making?"* of the *SETAC Europe 25th Annual Meeting* comes to a similar conclusion.

information cannot be found. Once this information is readily available, it should be integrated and be regarded as a mandatory requirement. At the moment however, it can only be an optional recommendation for future development.

Yes-no question: Is information on the uncertainty included in the output?

Documentation: Output of information on the uncertainty of environmental and RSL data.

2.3.4. Summary of Section 2.3

Which requirements are necessary for the output of results?

Requirements regarding the output relate to the user-friendliness and the applicability of the method. As they are not essential for the quality of the LCA results, all three requirements are optional:

- **Visualization of results (O):** A visualization should be provided to facilitate the communication of results. This can be documented by a screenshot of the graphic output.
- **Single-score indicator (O):** In addition to midpoint indicators, a single-score indicator should be provided for decision-makers. The underlying weighting method should be described in the documentation.
- **Information on data uncertainty (O):** If possible, information on the uncertainty of the LCA results resulting from the uncertainty in the environmental and RSL data should be included in the output. As this information is currently not typically available, it can only be a recommendation for the future.

2.4. Requirements regarding optimization

To carry out design optimization based on LCA in the design process, the following requirements are both mandatory:

- Self-contained workflow
- Maximum time for application

In addition to these mandatory requirements, which can be clearly defined, an optional requirement to evaluate the time-efficiency of the method is provided. Despite the high importance of this criterion, it is designated as optional, because measurement is difficult.

2.4.1. Self-contained workflow

Description: As described in Section 1.3.4, optimization in the architectural design process is based on a comparison of variants. Therefore, the generation and comparison of design variants is absolutely necessary. There are two approaches for design optimization: manual improvement by the architect or application of computational optimizers (see Section 1.3.4).

Both approaches have their advantages and disadvantages. The optimizer can generate and evaluate a lot of variants in a short space of time and, according to a test by Szalay et al. (2014, p.22), probably find a better solution than the architect's own experiments with manually generated variants. Therefore, the opportunity to employ computational optimizers should be provided.

However, if the architect is not familiar with the algorithms that drive the optimization process, it may appear to be a 'black box'. Furthermore, the architect needs basic knowledge about how to adjust the parameters to be varied by the optimizer to the specific boundary conditions for the design, such as required setbacks or specifications of the master plan. Besides, the automatically derived solution may not appeal to the architect for other reasons, such as aesthetic appearance or functional requirements. The optimization of a window layout on a building facade, for example, can be easily assigned to an optimizer. Exclusive use of the LCA results as an optimization criterion will probably lead to a solution that does not fulfil functional requirements, such as daylight availability or views to the outside, and might also not be satisfying in aesthetic appearance. Manually changing the design allows the architect to consider additional aspects and boundary conditions. These boundary conditions can also be integrated into the constraints of the computational optimizer, however, this implies a detailed knowledge of the optimizer. Therefore, the opportunity for manual design improvement should be provided as well. Manual generation of variants by the architect requires the opportunity to quickly adjust the geometry, building materials, and building services. The measurement of the time needed for adjustment is discussed in the requirement for *time-efficiency.*

Manual input and data import hinders the application of computational optimizers and results in unnecessary effort for manual adjustment. Therefore, it should be avoided. For both optimization approaches – the application of computational optimizers and manual adjustment – a self-contained workflow of the method employed is a crucial prerequisite.

Yes-no question: Is the method's workflow self-contained?

Documentation: Description of the calculation algorithms and the workflow of the method.

2.4.2. Maximum time for application

Description: As described in Section 1.4.3, the time needed for LCA depends on the method itself and the boundary conditions, including the size of the building, amongst others. This makes it difficult to define an exact maximum acceptable amount of time for the calculation of an LCA for a building. In the literature, no exact maximum time can be found. Most studies evaluate tools qualitatively and describe the time-efficiency with attributes like "quick data input" (Weytjens et al. 2011, p.2449) or "calculation time is short" (Meex et al. 2016, p.1313), for example. Other studies on building performance analysis state that the results have to be calculated and visualized in real time in order to serve as a design support tool (see Schlueter & Thesseling 2009, p.159; de Souza 2009, p.295), but do not provide a maximum acceptable amount of time for the input. Therefore, a maximum acceptable time for the application of the method can only be assumed here.

The Federal German Chamber of Architects recommends that its members do not spend more than 140 hours up to design stage 3 for a regular single-family house in order to work cost-effectively[62]. Considering all of the tasks that architects have to carry out, it is assumed that the maximum amount of time they can spend on an LCA for a building, including all data input and optimization, is one work day, respectively 8 hours, for a small to mid-size residential building. For very large or complex buildings, including mixed-use, two work days (16 hours) can be assumed as a realistic maximum time.

[62] The recommendations can be downloaded at http://www.byak.de/start/informationen-fur-mitglieder/downloadbereich#orientierungshilfen (accessed May 5th 2016)

Yes-no question: Is the time required for application of the method less than 8 hours for typical residential buildings and less than 16 hours for complex, mixed-use buildings?

Documentation: Declaration of the time required to apply the method.

2.4.3. Time-efficiency

Description: Although very important, this requirement is described last, because it is based on many of the requirements described previously. As described in Section 1.4.3, the time-efficiency of an environmental design optimization method can be defined as the ratio between the reduction in environmental impact and the time needed for the application of the method. In order to measure time-efficiency, both the reduction in impact due to application of the method and the time needed for its application have to be measured.

To measure the reduction in impact, the optimized solution can be compared to a benchmark or a baseline solution. Benchmarks can be found in the literature, for example Braune (2014, p.173) or König et al. (2010, pp.52-57), or in guidelines for building certification systems. An overview is provided by Wittstock et al. (2012, pp.348–351). In the case of a building refurbishment, the design variant can be compared to the original state of the building. As the reduction in impact is highly dependent on the choice of the baseline scenario employed, this requirement is recommended as an optional criterion for evaluating an environmental building design optimization method, but no minimum reduction is prescribed. Furthermore, for reasons of transparency, the reference values should be communicated clearly.

The time required for input, calculation, and output of the first variant varies significantly from the calculation of the following variants for the commercial LCA tools for buildings analysed in Section 1.4.2.1. Therefore, when measuring the time needed for application of the environmental building design optimization method, a distinction is made between the time necessary for the first variant and the time required for the further variants developed to optimize the design. Furthermore, based on the recommendations of Schlueter & Thesseling (2009, p.159) and de Souza (2009, p.295), the optional recommendation is that the calculation itself should occur in real-time in order to allow the architect to receive direct feedback during the design process.

Optional questions: a) How much can the environmental impact be reduced?
b) How much time is needed for the first design variant?
c) How much time is needed for the optimization process?

Documentation: a) Description of the baseline scenario and declaration of the improvement.

b) Declaration of the time required for the first variant and the boundary conditions, including the experience level of the user, the type of building, and the performance of the computer employed.
c) Declaration of the time required for optimization and the number of variants analysed.

2.4.4. Summary of Section 2.4

Which requirements are necessary for optimization?
To carry out design optimization based on LCA in the design process, the two following requirements are mandatory:

- **Self-contained workflow (M):** To allow for optimization using computational optimizers and to facilitate manual improvement, the method's workflow needs to be a closed loop. This can be demonstrated by describing the calculation algorithms and the workflow of the method.
- **Maximum time for application (M):** It is assumed that, in order to be applicable to the design process in architectural practice, the time needed for application of the method needs to be less than 8 hours for typical residential buildings, and less than approximately 24 hours for complex mixed-use buildings. The time required should be documented, including a description of the boundary conditions for applying the method, such as the performance of the computer or the experience level of the user.
- **Time-efficiency (O):** In addition to the mandatory requirement to set a time limit for application, time-efficiency can be assessed by measuring the reduction in environmental impact compared to the time needed for the optimization process. As the reduction in impact is highly dependent on the choice of benchmark, considering time-efficiency is recommended as an optional criterion only, despite its importance.

2.5. Summary of Chapter 2

Which requirements for environmental building design optimization methods can be derived from the analysis?

The requirements derived from the analysis are summarized in the form of a checklist in Table 25. An indication is provided as to whether a requirement is mandatory (M) or optional (O). An additional table is provided for quantifying the optional recommendation for time-efficiency (see Table 26).

Table 25: Checklist of requirements for environmental building design optimization methods based on LCA

Step	Requirement	*	Question	Y	N	Documentation
Input	Life cycle modules	M	a) Screening LCA: Are at least the life cycle modules A1-A3, and B6 included? b) Simplified LCA: Are A1-A3, B4, B6, C3, C4, and D included?			Declaration of life cycle modules included
	Environmental indicators	O	a) Screening LCA: Are at least three indicators covering different environmental problem fields included? b) Simplified LCA: Are PET, PENRT, GWP, EP, AP, ODP, and POCP included?			Declaration of environmental datasets employed and output of the respective indicators
	Environmental data quality	M	Is the environmental data valid?			Declaration of environmental datasets employed
	Minimum building components to be included in the 3D model	M	a) Screening LCA: Are the building envelope and the primary load-bearing structure included? b) Simplified LCA: Are exterior walls, windows, roofs, ceilings, slabs, foundations, interior walls, columns, and building services included?			Screenshot of the 3D model and description the components included
	Reference Study Period	M	Is the assumed RSP declared?			Declaration of the RSP
		O	Can the RSP be adjusted?			Description of the adjustment
	Predefined values	O	Are predefined data based on the most typical building components provided?			Declaration of predefined values
Calculation	Combined calculation of I_E and I_O	M	Are the modules of I_E (A1-A3, B4, C3, C4 and D) and of I_O (module B6) linked and calculated together?			Description of the calculation algorithms
	Operational energy demand	M	Is the energy demand for space heating and cooling calculated using at least monthly time steps?			Description of the method used for energy calculation including the time steps
Output	Visualization of results	O	Is a graphic output provided?			Screenshot of graphic output
	Single-score indicator	O	Is a single-score indicator output in addition to the midpoint indicators?			Output of a single-score indicator and description of the weighting method
	Information on data uncertainty	O	Is information on the data uncertainty included in the output?			Output of information on the uncertainty of environmental and RSL data
Optimization	Self-contained workflow	M	Is the method's workflow self-contained?			Description of the calculation algorithms and the workflow
	Maximum time for application	M	Is the time needed for application less than 8 hours for residential buildings / 16 hours for complex buildings?			Declaration of the time needed to apply the method

* Mandatory (M) or optional (O) requirement

Table 26: Checklist for measuring time-efficiency

Question	Documentation
How much environmental impact can be saved?	Description of the baseline scenario and declaration of the improvement
How much time is needed for the first design variant?	Declaration of the time needed for the first variant and the boundary conditions including the experience of the user, the type of building and the performance of the computer employed
How much time is needed for the optimization process?	Declaration of the time needed for optimization and the amount of variants analysed

Both tables can be used as checklists for evaluating environmental building design optimization methods. If a method does not fulfil all mandatory requirements, it cannot be regarded as suitable for application in the design process. The existing commercial tools analysed in Section 1.4.2.1 do not provide a self-contained workflow and therefore do not fulfil the mandatory requirement for optimization. The academic approaches described in Section 1.4.2.2 are not publicly available, and no declaration of the time needed for application could be found in the literature. As such, it is not possible to evaluate them using the checklist. The checklist can be used to evaluate potential environmental building design optimization methods developed in the future. In this thesis, the checklist will serve as guideline for the development of the parametric method described in Chapter 3 and its evaluation in Chapter 4.

3. Development of a parametric method for time-efficient environmental building design optimization

An analysis of the state-of-the-art of LCA for buildings indicates that the intricate calculation requires computer assistance. However, existing computer-aided LCA approaches for buildings (see Section 1.4.2) are not suitable for the architectural design process - mainly, because they lack the potential for time-efficient design optimization. Sections 1.3.3 and 1.3.4 showed that parametric design provides many opportunities for time-efficient design optimization. Therefore, the key idea proposed in this thesis is to combine LCA with the principles of parametric design to make use of this potential for environmental design optimization. The proposed solution for closing the research gap described in Section 1.4.4 is a time-efficient method for environmental building design optimization based on a digital, parametric LCA model. This method is called *Parametric Life Cycle Assessment* (PLCA).

This chapter describes the development of PLCA and consists of three sections. The first section describes the characteristics of the parametric method. The method cannot be applied unless it is implemented in a software tool. Therefore, the second section describes implementation using parametric design software. The resulting parametric tool is called CAALA – Computer-Aided Architectural Life cycle Assessment. The third section focusses on the verification of the algorithms developed in the first section and implemented in the tool in the second section. To verify the algorithms, a reference building was modelled and the results provided by CAALA were compared to those of a study published by Hartwig (2012).

Beginning in the early design stages, PLCA can be applied throughout the entire design process. More detailed information can easily be added in the later stages of the design process, continuously extending the model from a screening type to a complete LCA. This thesis focusses on the application of LCA during the design process. Therefore, only the screening and simplified LCA are covered in detail. Nevertheless, PLCA can be similarly employed for all life cycle modules.

3.1. Parametric LCA model

The key element of the proposed method is a digital, parametric LCA model. The model has been developed according to the requirements described in Chapter 2. The general workflow of optimization introduced in Section 1.3.4 (see Figure 18) is also incorporated into the PLCA workflow. As such, the workflow can also be divided into the following four steps:

1. Input
2. Calculation
3. Output
4. Optimization

The schematic structure of the parametric LCA model and the workflow are shown in Figure 22. The figure shows the most important characteristic of the model: all steps and all components within those steps are interlinked and form a closed calculation loop. This provides the basis for optimization. Each step is described in detail in the following sections.

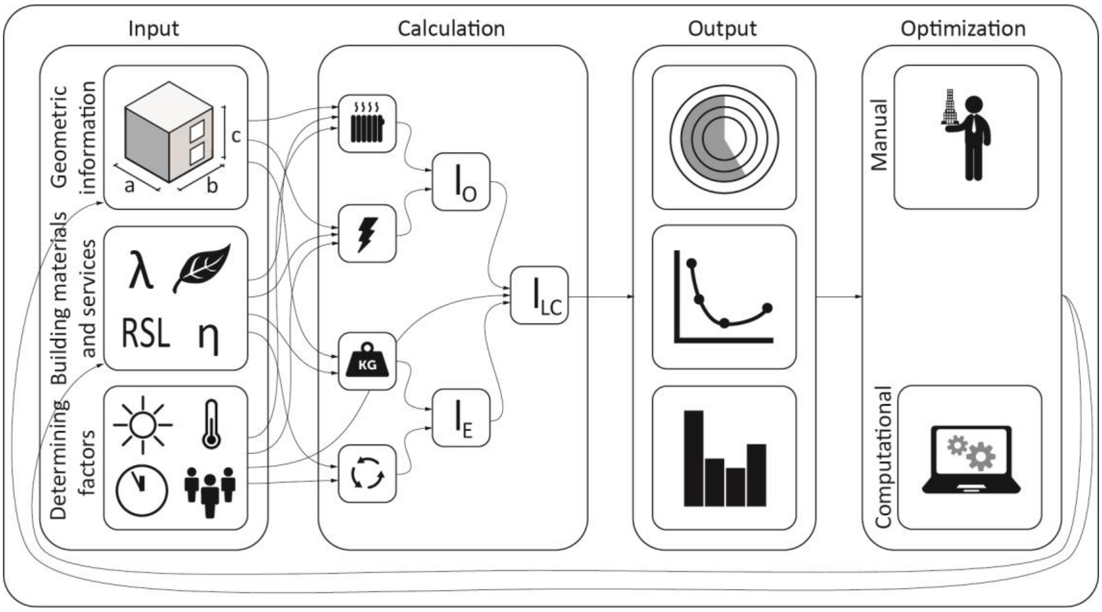

Figure 22: Schematic structure of the workflow of PLCA

3.1.1. Input

The basic prerequisite for the parametric model is the parametrization of all input. This is necessary for a closed optimization loop as shown in Figure 22 and for the application of computational optimizers. Furthermore, it also facilitates manual variation by permitting quick adjustment and variation of all input parameters.

To structure the input, it is divided into three categories:

1. Geometric information
2. Building materials and services
3. Determining factors

The three categories are described in the three parts of this section.

3.1.1.1. Geometric information

There are two options to input geometric information. The first option is to input the geometry using a drawn 3D CAD model. In contrast to common architectural models with building components made of 3D elements (solids), it only consists of 2D elements (surfaces) (see Figure 23).

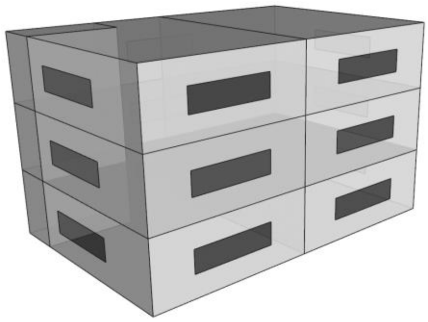

Figure 23: Simplified building representation using surfaces only

This approach is commonly employed in thermal models for energy demand calculation. Throughout the design process, the level of detail of the geometric model remains at the simple, single surface model. The higher level of detailed information for later design stages is added through the definition of non-geometric information – namely building materials and services.

When using this approach, the question arises as to where to position this simplified surface in relation to the three dimensional wall geometry. Here, the typical approach of using the outer edge of exterior walls and the centre line of interior walls is employed (cf. SIA 2040:2011, p.15). Two examples of this simplified representation for an exterior wall and an interior wall are provided by Figure 24 and Figure 25 respectively. Both figures visualize the representation using a) a solid and b) a surface. The third dimension of each building component is added by inputting the thickness numerically - variable x in Figure 24(c). On the one hand, this has the advantage that modelling the geometry is much faster, and material thicknesses can be modified easily and quickly. Furthermore, this approach allows computational optimizers to define the insulation thickness. On the other hand, this simplification introduces certain inaccuracies, for example when calculating the masses. The volume and the resulting mass of inner layers are therefore overestimated as shown in (c). Here, this is not considered problematic, because the method aims for application in the early design stage. If the same model is to be used for a complete LCA in future, the exact volumes could be calculated through intersection. This is not implemented here to reduce the complexity. Furthermore, inaccuracies will be caused in the construction process at the building site. For example, a masonry wall will require the bricks to be cut to fit, causing additional waste. The inaccuracies introduced by this simplified modelling can therefore be neglected.

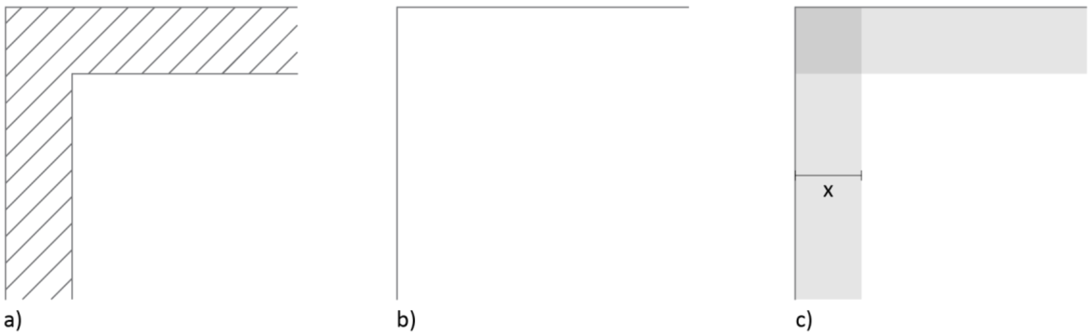

Figure 24: Simplified representation of an exterior wall

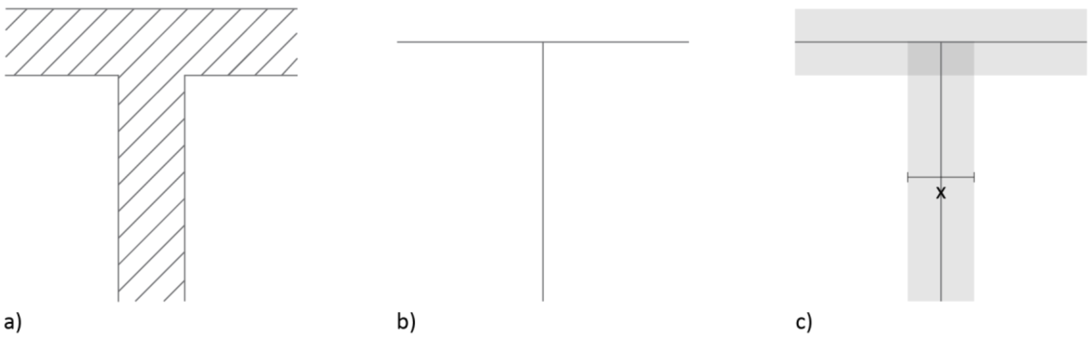

Figure 25: Simplified representation of an interior wall

For a screening LCA, the input of interior walls can be further simplified by using a global factor instead of modelling each interior wall. Minergie (2016, p.5) recommends using a factor based on three different typical floorplans (see Table 27).

Table 27: Global factor for interior walls, based on values provided in Minergie (2016, p.5)

Floor plan type	Average room size [m²]	Factor for interior walls [length of interior walls in m/floor area of conditioned zones in m²]
Few walls	48	0.25
Moderate number of walls	20	0.4
Many walls	12	0.5

In the second option, the geometry is directly modelled parametrically using parametric design software instead of drawing the 3D model. This requires a certain knowledge on the part of the architect in using this kind of software, but allows for the quick generation of many geometric variants.

In both cases, the information necessary for the calculation of the LCA, such as the area of each surface, is extracted from the geometric model. The orientation and inclination of each surface required for the energy demand calculation are extracted as well.

3.1.1.2. Building materials and services

The necessary non-geometric information consists of the definition of building materials and building services. As shown in Section 1.2.2.4, numerous data are needed for the LCA of a building. Data required for material definition can be divided into three categories: environmental data, reference service life (RSL) data, and physical properties. At present, there is no database available which contains all three kinds of necessary data[63]. Therefore, a combined database has been developed for this thesis. It consists of one spreadsheet with data in the three categories. Table 28 shows its structure for the example of concrete.

Table 28: Combined database for the example of concrete

		Physical properties							Environmental data																
									Production (A1-A3)								End of Life (C3, C4, D)								
Name	Unit	Density [kg/m³]	Roughness	Thermal conductivity [W/m·K]	Specific Heat Capacity [J/kg·K]	Thermal Absorptance	Solar Absorptance	Visual Absorptance	PERT [MJ]	PENRT [MJ]	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3-}-e]	ADPe [kg Sb-e]	PERT [MJ]	PENRT [MJ]	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3-}-e]	ADPe [kg Sb-e]	RSL [a]
Concrete C 20/25	1 kg	2365	rough	1.65	1000	0.9	0.6	0.6	0.00873349	0.47924101	0.09196017	2.4949E-09	0.00016641	2.3628E-05	1.6934E-05	0.00019408	0.00213811	0.05348733	0.00271666	1.8977E-12	2.5344E-05	4.4323E-06	2.6919E-06	2.4921E-05	50

[63] Stephan Rössig, the developer of eLCA, mentioned during a meeting in August 2015 that the integration of physical properties is possible in theory, but the manufacturers have to upload their specific data. This will probably take a few years till a completed dataset can be achieved.

In general, any environmental data can be employed within the parametric model. Here, the German *ökobau.dat*[64] is used, because it is the standard in Germany and also used for German building certification systems. In addition, it is one of the most developed databases in Europe. Currently, only German data is integrated, but discussions are ongoing to include data from other European countries in ökobau.dat in the near future[65]. The data of öko-bau.dat consist of EPDs and generic data. All of them declare modules A1-A3 together. Modules A4-A5 are very rarely declared and modules C1 and C2 are not declared. Some datasets include the modules C3, C4 and D, but most of the time the scenario for the end-of-life (EOL) has to be chosen by the user. For several EOL s, these modules are declared separately and the assignment of the right EOL is sometimes difficult, because it is based on assumptions and depends on the user's choice. The online tool *eLCA*[66] is the standard tool for BNB certification. It employs data from ökobau.dat version 2011 and has pre-assigned EOL data, including modules C3, C4 and D[67]. Therefore, these datasets are exported from eLCA and used here. The 2015 version of ökobau.dat has not yet been integrated into eLCA[68], but once it has been integrated it can be similarly employed.

As shown in Section 1.2.2.4, the RSL has a large influence on the LCA results, because it defines the number of material replacements during the building's life cycle. The exported list of materials from the eLCA tool also incorporates RSL data from BBSR[69]. To ensure

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[64] The online database ökobau.dat contains more than 700 different building products and complies with EN 15804:2012. It is provided by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety and can be accessed at http://oekobaudat.de/ (accessed March 12th 2016)

[65] This information was provided by the Bundesinstitut für Bau-, Stadt-und Raumforschung (BBSR) at the conference Sustainable Build Environment in March 2016 in Hamburg.

[66] eLCA is a free German online tool provided by Bundesinstitut für Bau-, Stadt-und Raumforschung (BBSR) and can be accessed at http://bauteileditor.de/ (accessed March 6th 2016)

[67] In the ökobau.dat version 2015 module D is declared separately. eLCA did not yet incorporate this data in March 2016, but according to Stephan Rössig from BBSR it will be included soon. Once the 2015 version is integrated, the exported configuration will declare module D separately, too.

[68] As at March 2016.

[69] The table with RSL data used for BNB certification system is called *Nutzungsdauern von Bauteilen zur Lebenszyklusanalyse nach BNB* and is provided by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (Bundesinstitut für Bau-, Stadt- und Raumforschung - BBSR) It can be download-ed at http://www.nachhaltigesbauen.de/baustoff-und-gebaeudedaten/nutzungsdauern-von-bauteilen.html (accessed March 12th 2016)

comparability, this list serves as the default data here. More detailed RSL data provided by Ritter (2011, pp.225-234) or any other source can be similarly integrated.

As PLCA is developed for the early design stages, specific manufacturers are unknown, and generic data must be employed. Different densities for generic data are provided by ökobau.dat, as noted in Section 1.2.2.4. To reduce uncertainty based on the choice of the density, the same density as in eLCA is used here. The physical properties are taken from DIN 4108-4:2013 and matched with the densities of the environmental data from eLCA.

Input of the building components and materials usually requires a lot of time and effort. Especially in the early design stages, the LCA should be carried out very quickly in order to be applied in practice. Thus, the screening LCA approach presented here proposes to employ a predefined building component catalogue to further simplify the input. The building component catalogue is established based on the most typical types of construction. This catalogue provides default values for the early design stages, which avoids problems associated with a lack of input parameters while carrying out the calculation. The basic idea is that the architect only has to choose one of the components provided in the catalogue. The thickness of each material within the building component is predefined according to statistical values.

All components which are part of the thermal building envelope (exterior wall, roof, and slab/basement ceiling) are defined using two layers. Layer A consists of all materials with predefined thicknesses except the insulation material. Layer B consists of the insulation material with a variable thickness (see Figure 26 for examples of an exterior wall). The insulation layer significantly defines the energy standard of the building envelope and the amount of transmission heat loss. Therefore, it is an important parameter to define the trade-off between operational and embodied impact. For monolithic constructions, e.g. light weight concrete, Layer A is set to zero and Layer B defines the material. The thickness of the whole component can be controlled through the thickness of layer B (see Figure 26c).

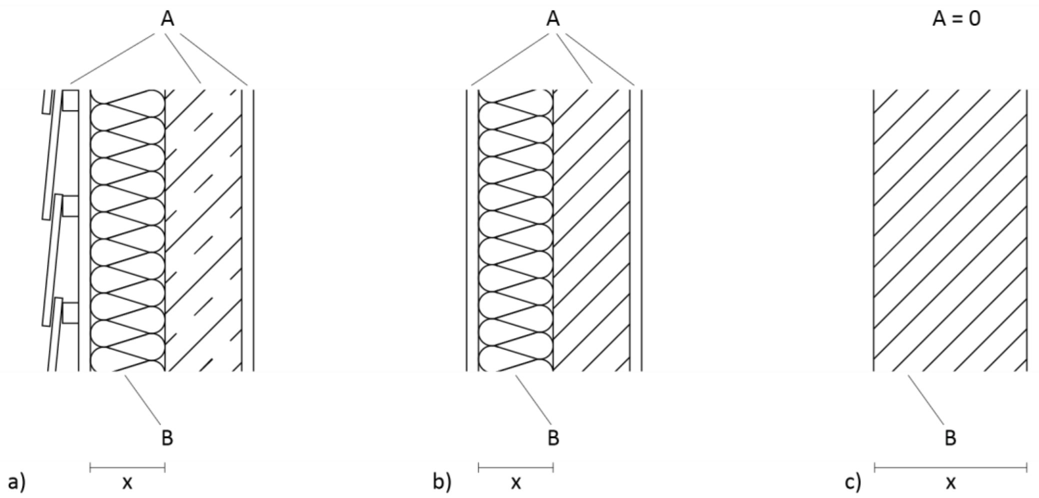

Figure 26: Examples for simplified component input: a) ventilated façade with wooden cladding and reinforced concrete wall, b) External Thermal Insulation Composite System (ETICS) on lime sand stone, c) monolithic light weight concrete

Other building components are defined using one fixed layer A. The building component catalogue is structured according to the following nine categories:

1. Exterior walls
2. Roofs
3. Foundations and slabs
4. Ceilings
5. Load-bearing interior walls
6. Columns
7. Windows
8. Non-load-bearing interior walls and doors
9. Building service components

The catalogue is based on a range of typical building components in Germany and can be extended in the future.

The building catalogue can also be employed for simplified LCA. However, for components with a large influence on the embodied impact, such as the building envelope and the primary structure, all material layers defining the component should be input separately. Of course, other components with less influence can also be modelled in higher detail. An overview of recommendations for the input of building materials and services is provided in Table 29.

Table 29: Recommendations for input of building materials and services for screening and simplified LCA

	Screening LCA	Simplified LCA
Exterior walls	Component catalogue, variable insulation thickness	Simplified modelling of all layers
Roof	Component catalogue, variable insulation thickness	Simplified modelling of all layers
Foundation and slab	Component catalogue, variable insulation thickness	Simplified modelling of all layers
Ceilings	Component catalogue	Simplified modelling of all layers
Load-bearing interior walls	Component catalogue	Simplified modelling of all layers
Columns	Component catalogue	Component catalogue
Windows	Component catalogue	Component catalogue
Non-load-bearing interior walls and doors	Optionally (depending on goal definition) / component catalogue	Component catalogue
Building service components	Optionally (depending on goal definition) / component catalogue	Component catalogue

In most cases, the rough geometry is defined in stage 2 of the design process, while the material is defined in detail in stage 3 or 4. To avoid the dilemma described in Section 1.3.1, PLCA employs default building materials and services from the component catalogue in order to calculate the I_{LC} before the materials and building services have been finalized. Once the materials and building services have been decided, the same model can be used with detailed environmental data for new materials, e.g. EPDs. In some cases, building materials have been decided beforehand, for example, if the client specifies a timber construction. In this case, the architect can choose the specific material and then start the geometric design process.

3.1.1.3. Determining factors

The data required for the determining factors can be divided into three categories:

- **Climate data:** The input of climate data depends on how the operational energy demand will be calculated, as described in Section 1.2.2.4. For both QSSM and DBPS methods, the respective climate data is loaded into the model.
- **User data:** Here, user data from DIN V 18599-10:2011 is employed and loaded into the model. Any other user data could be similarly integrated. An experienced user can also numerically input their own user data and adjust it parametrically.

- **Reference study period:** The reference study period (RSP) is entered numerically, depending on the scope of the LCA. The parametric input allows for the quick comparison of different RSPs.

3.1.2. Calculation

The approach presented here combines the primary energy demand and environmental impact of the building in the term *impact*. It distinguishes between the *operational impact* (I_O) resulting from the operational energy use of the building (module B6) and the *embodied impact* (I_E) resulting from production and the EOL of the building (modules A1-A3, C3, C4, and D). The replacement of building components (module B4) is also considered as I_E. The *life cycle impact* (I_{LC}) is the sum of I_E and I_O (see Equation 1). While this is a general formula, only the life cycle modules indicated in Table 22 are integrated in the calculation in this thesis.

$$I_{LC} = I_O + I_E \tag{1}$$

3.1.2.1. Operational impact

First of all, the energy demand in the use phase has to be known for the calculation of the operational impact (I_O). PLCA differentiates between energy demand influenced by the building design and energy demand mostly influenced by the user. The first kind is calculated specifically for each individual design, while the latter kind is integrated using statistical data based on user profiles. The design-influenced energy demand can be calculated either using QSSM or DBPS. This option is provided, because both approaches have their advantages and disadvantages, as shown in Section 1.2.2.2. In both cases a thermal model is needed, which is automatically extracted from the geometric model. As described in Section 1.2.2.2, QSSM is much more time-efficient for optimization based on many design variants. Therefore, the parametric energy demand calculation based on DIN V 18599-2:2011 (Lichtenheld et al. 2015, pp.1-3) is employed in the early design stages where possible.

I_O consists of the sum of all different kinds of *operational energy demand* during the use phase (ED_i) divided by the *performance factor* (PF_i) for the specific building services and multiplied by the *operational impact factor* of the energy carrier ($IF_{O,i}$) (see Equation 2). ED refers to the useful energy demand and is calculated with reference to one year of operation. Therefore, the sum is multiplied by the number of years of the reference study period (RSP). The PF is introduced to describe different types of building services with one systematic method. It depends on the performance of the building service employed, such as the annual performance factor (APF) for a heat pump or the efficiency for a gas-condensing boiler, and includes all different kinds of losses within the building. The greater the PF, the lower the resulting I_O. ED divided by PF equals the amount of final energy which enters the building. The operational impact factor (IF_O) is imported from the combined database. It depends on the energy carrier employed and the indicators chosen for the LCA. For primary energy it is also called the *primary energy factor*. For example, the PENRT equals 8.775 MJ for 1 kWh of electricity in the European mix in the year 2008.

$$I_O = \sum_i (ED_i \, / \, PF_i \times IF_{O,i}) \times RSP \tag{2}$$

3.1.2.2. Embodied impact

The embodied impact (I_E) is calculated by multiplying the mass of each material (M_j) by the specific *embodied impact factor* of the material ($IF_{E,j}$) (see Equation 3). To determine the mass, first of all, the areas of the different building surfaces have to be calculated. The surface areas are then multiplied by the thickness and density of the specific material. The density is imported from the combined database, together with the RSL and the specific IF_E. In this way, the I_E of every component is calculated and summed up to obtain the I_E of the entire building.

$$I_E = \sum_j (M_j \times IF_{E,j} \times (1 + R_j)) \tag{3}$$

If the RSL of a building component (RSL_j) is lower than the RSP of the building, the necessary number of replacements (R_j) is considered (see Equation 4). For example, if a coating possesses a RSL of 20 years, it has to be renewed twice within an RSP of 50 years, so R equals 2.

$$R_j = \lceil RSP/RSL_j \rceil - 1 \tag{4}$$

The impact factors ($IF_{O,i}$, $IF_{E,j}$) depend on the indicator chosen for the LCA. If more than one indicator is used, the impact factors are written as vectors of the indicators applied. In consequence, the resulting impact (I_O, I_E) is a vector as well. The advantage of using vectors for the impact factors is that the indicators chosen for evaluation can be easily modified depending on the available data. Equation 5 shows $IF_{O,i}$ and $IF_{E,j}$ for the eight indicators used for DGNB certification. When using the Swiss database for building materials

(*Ökobilanzdaten im Baubereich*) provided by KBOB[70] for example, only three indicators, namely PENRT, GWP, and UBP are available, resulting in a vector with three entries.

$$IF_{O,i} = \begin{pmatrix} PET \\ PERT \\ PENRT \\ GWP \\ EP \\ AP \\ ODP \\ POCP \end{pmatrix}, IF_{E,j} = \begin{pmatrix} PET \\ PERT \\ PENRT \\ GWP \\ EP \\ AP \\ ODP \\ POCP \end{pmatrix} \quad (5)$$

All terms of the equations are assumed to be static, although some values might change in the future, for example the PF of the building services. Furthermore, the electricity mix will change, and as a result the environmental data of the material will also change. Replaced building components will then have a lower embodied impact. These considerations are neglected here, but they could be integrated into the equations in future, leading to a dynamic LCA.

3.1.3. Output

The aim is to provide the architects with insight into the environmental impact of their design and indicate potential for improvement. Therefore, it is not only important to output numerical results, but also to display the results graphically in an easily comprehensible manner for non-LCA-experts. In addition, the results can be exported to spreadsheets for further use, such as for building certification.

3.1.3.1. Numerical Results

The results of the I_{LC} are reported according to the vectors of the impact factors ($IF_{O,i}$, $IF_{E,j}$). In addition to the final results of the LCA, partial results, such as I_O for heating or the I_E of windows, can be output separately. As such, very high values in partial results can indicate potential for improvement. In addition, the results and the calculation method are made transparent.

[70] The dataset Ökobilanzdaten im Baubereich with explanations can be downloaded at http://www.eco-bau.ch/resources/uploads/Oekobilanzdaten/kbob-Oekobilanzdaten-Empfehlung_29_07_2014.pdf (accessed March 12th 2016)

In general, the results should be presented in a way that is understandable for users that do not have detailed knowledge of LCA. Often, absolute results are not meaningful to non-experts: for example, a client is probably unable to interpret the statement "your building design has an acidification potential of 0.3 kg SO_2-equivalent/m² a". A more promising approach is to use the results of the LCA to compare different design variants. It is far easier to communicate that design A possesses 3.7 t CO_2-equivalent less GWP than designs B and C while providing the same function. The client can then make an informed decision taking other parameters into consideration, such as costs.

Normalization, weighting, and aggregation of several indicators into a single score is also possible. The parametric approach allows the advanced user to define and adapt their own weighting factors in order to take the specific goals of the LCA study into consideration. Furthermore, it allows different predefined weighting factors to be employed, such as those of a particular building certification system. In this case, it allows architects to optimize the building design to score the most points in the certification system. This is illustrated using a new residential building and DGNB certification as an example in Section 4.2. In addition to the aggregated and weighted results, the individual midpoint indicators are reported separately to conform to ISO 14040:2009.

3.1.3.2. Visualization

Architects are accustomed to working on the basis of visual information. Therefore, graphical representation of the LCA results is very important. The means for displaying the results are not a key part of this thesis and would go beyond its scope, but some examples of representation are used in the examples in Chapter 4. These consist of different bar and pie charts to indicate potential for improvement.

3.1.4. Optimization

As noted in Section 1.3.4, architects have two options for optimizing a building design. They can either manually vary parameters and improve the design iteratively, or apply computational optimizers. As Figure 22 indicates, the parametric model provides both options for improving a design for minimum I_{LC}.

For the computational approach, evolutionary algorithms (EA) are chosen because of their suitability for problems with little background knowledge. To optimize for more than one objective and find the trade-off between conflicting objectives, evolutionary multi-criteria optimizers (EMO) can be employed. The visualization of the Pareto front can be a valuable means to provide a basis for deciding on conflicting objectives. This is shown in Section 4.1.5 for the example of the trade-off between GWP_{LC} and investment costs.

As described in Section 2.4.1, both approaches have their advantages and disadvantages. To make use of the advantages of both approaches, a combination is proposed. Computational optimizers are employed for certain decisions where the objective can be clearly defined and the influence on other criteria is negligible, e.g. the optimization of the thickness of an insulation material. Parameters with a large influence on other criteria, such as appearance or functionality, are varied manually. The window layout, for example, significantly influences functional criteria such as daylight availability, views to the outside, and the appearance of the whole building. In this case a manual variation might lead to solutions that satisfy architects and clients faster and reduce the environmental impact while preserving those qualities. The detailed development of such a semi-automated method would go beyond the scope of this thesis, but the application of a semi-automatic approach is briefly illustrated in Section 4.2.

3.1.5. Summary of Section 3.1

What is the key element of the parametric method and how is the input parametrized?

The key element of the proposed method called *Parametric Life Cycle Assessment* (PLCA) is a digital, parametric LCA model. The workflow involved in employing the model can be divided into four steps: input, calculation, output, and optimization. The unique and most important characteristic of the model is that all four steps and all components within those steps are interlinked and form a closed calculation loop. This provides the basis for optimization.

The basic prerequisite for the parametric model is the parametrization of all input. To structure the input, it is divided into three categories: *geometric information*, *building materials and services,* and *determining factors*. To input the geometry, either a simple 3D model can be used, from which the necessary parameters are extracted automatically and transferred to the LCA model, or the geometry can be directly modelled using parametric design software. To input building materials and services, three kinds of data are necessary: environmental data, RSL data, and physical properties. To simplify the input, a combined database is established. Environmental data is based on ökobau.dat, typical RSL data are exported from the eLCA online tool, and physical properties like conductivity are taken from DIN 4108-4:2013. To further simplify the input for screening LCA, a component catalogue based on this combined dataset is provided. Determining factors, such as climate or user data, are taken from standards and employed by the model. The RSP is also defined parametrically. All necessary input is parametrized and can quickly be varied for optimization purposes, either manually by the architect or by a computational optimizer.

Which algorithms were developed to calculate the LCA?

A distinction has been made between *operational* and *embodied impact* (I_O and I_E). Both are calculated separately but simultaneously and then added together to provide the *life cycle impact* (I_{LC}). The operational impact consists of the sum of all different types of energy demand during the use phase divided by a performance factor for the specific building services, multiplied by the impact factor of the energy carrier, and multiplied by the number of years of the reference study period (RSP). Within this step, the energy demand is directly calculated using QSSM or DBPS to avoid the exporting and importing that is necessary for conventional approaches. The embodied impact of one material is calculated by multiplying the mass by the specific impact factor of the material and by the number of replacements. In this way, the embodied impact of every component is calculated and summed up to generate an embodied impact for the complete building.

What allows for an easily comprehensible output of the LCA results?

To provide architects with insight into the environmental impact of their design and indicate potential for improvement, partial results are output in addition to the overall results. Different graphical representations of the LCA results can be output in addition to the numerical output to provide an easily comprehensible means for non-LCA-experts. Furthermore, the results can be exported to spreadsheets for further use, such as for building certification.

Which approaches to optimize the building design does the method provide?

The parametric model provides both possibilities for optimizing a design for minimum life cycle impact: manual variation of parameters by the architect or application of computational optimizers. The approaches can also be combined to make use of the advantages of both approaches. Computational optimizers are employed for certain decisions with a clear objective, while other parameters with a large influence on qualitative criteria are varied manually.

3.2. Implementation using parametric design software

In order to apply the parametric LCA model for the evaluation in Chapter 4, it has to be implemented using parametric design software. Any software for parametric design which is based on a 3D model can be employed for implementation. In this thesis, *Grasshopper3D*[71] (GH) is used, a parametric design software program based on the 3D CAD Software *Rhinoceros*[72]. The parametric tool is named CAALA – Computer-Aided Architectural Life cycle Assessment. Both the calculation of the energy demand and of the embodied impact are fully integrated into GH, making exporting and re-importing unnecessary. In this way, CAALA is able to calculate the LCA in real time. Figure 27 shows a screenshot of the user interface of Rhinoceros with CAALA.

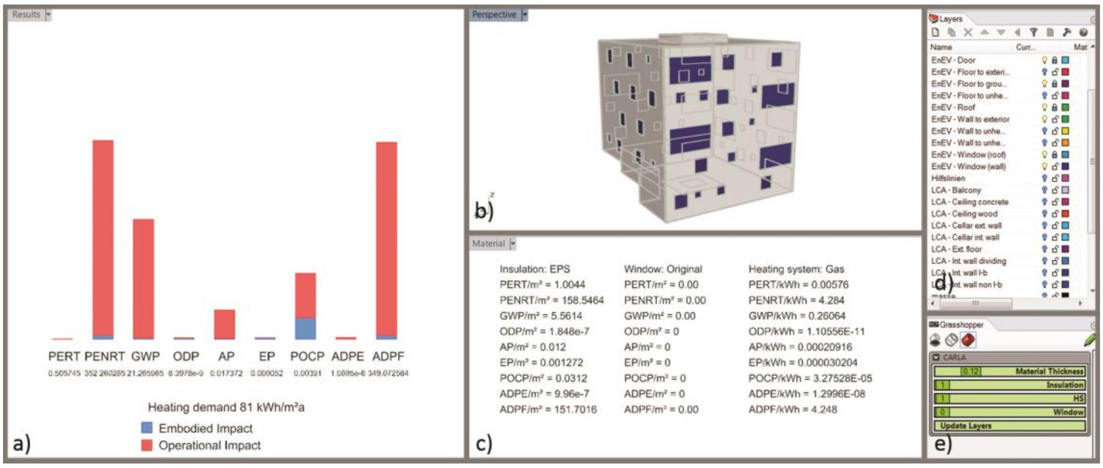

Figure 27: Screenshot of Rhinoceros with CAALA with different viewports: a) LCA results, b) 3D drawing of geometry, c) Material control, d) Layers of geometry, e) GH control for parametric adaptation

3.2.1. Input

The geometry can either be directly described parametrically in GH or drawn in Rhinoceros and then transferred automatically to GH. To automatically generate the thermal model, the different surfaces are drawn on pre-defined layers (see Figure 27d). Non-geometric parameters are defined in GH, including building components with materials and thicknesses and building services. Different means of inputting the data can be employed, such as drop-down lists and number sliders (see Figure 28). These can be linked to Rhinoceros to facilitate

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[71] Grasshopper3D is a graphical algorithm editor for 3D CAD software Rhinoceros and can be downloaded at http://www.grasshopper3d.com/page/download-1 (accessed March 14th 2016)

[72] Rhinoceros is a 3D CAD software based on NURBS, see https://www.rhino3d.com/ (accessed March 14th 2016)

adjustment while designing (see Figure 27e). If the user does not define these parameters, default values based on typical building materials and services are employed. The necessary data is imported from the combined database described in Section 3.1.1.2.

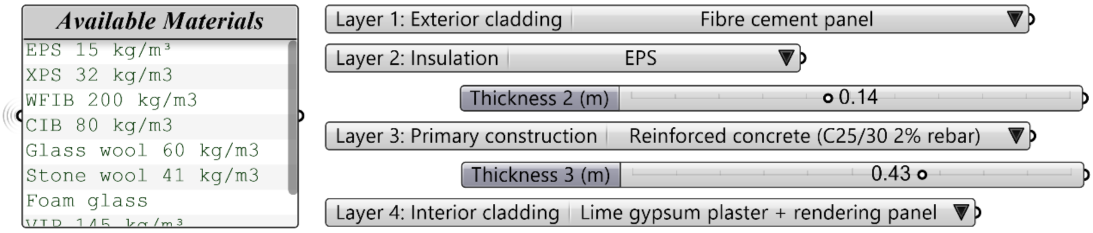

Figure 28: Example of parametric material definition in GH

3.2.2. Calculation

For the calculation of the energy demand based on QSSM, a plug-in for GH based on DIN V 18599-2:2011 has been developed for this thesis. All main parts of the standard relevant to residential buildings have been implemented in GH and allow for calculation of the energy demand in real time[73]. Development and verification of this implementation are described in Lichtenheld et al. (2015, pp.1-3). To enable the application of DBPS within CAALA as well, an existing plug-in called *Archsim*[74] is integrated, which uses the *EnergyPlus*[75] simulation engine. As such, cooling demand and the influence of shading measures can be simulated in detail.

3.2.3. Output

The results are displayed in the Rhinoceros viewport and can simultaneously be exported to a spreadsheet. Rhinoceros possesses multiple viewports, which allows the user to draw and change the geometry in one (see Figure 27b) and receive feedback on the results on a second one in real time (see Figure 27a). The results can be displayed in different ways, including numerical and graphical representation such as bar charts and pie charts. Further viewports can be used to control the input and display the non-geometric information (see Figure 27c).

[73] On a standard PC the calculation and output of results takes 0.1 seconds.

[74] ArchSim is a plug-in to link EnergyPlus with Grasshopper3D. It is developed by Timur Dogan and can be downloaded from http://archsim.com/downloads/ (accessed February, 9th 2016)

[75] EnergyPlus is an open source whole building simulation software funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), and managed by the National Renewable Energy Laboratory (NREL). The software is available at https://energyplus.net/downloads (accessed February, 9th 2016)

3.2.4. Optimization

In GH an optimizer using evolutionary algorithms (EA) called *Galapagos*[76] is implemented. The architect can define free parameters to be varied by assigning them to the optimizer using number sliders. The range of a number slider defines the range in which the optimization algorithm can vary the corresponding input parameter. The objective function can be defined for the minimization of a numerical output assigned to the optimizer (see Figure 29). In addition to Galapagos, further plug-ins from third party developers are available. *Goat*[77] provides five optimization algorithms including global EA and local, derivative-free optimizers. *Octopus*[78] provides the possibility to optimize for multiple criteria. The Pareto front is directly visualized during the optimization process.

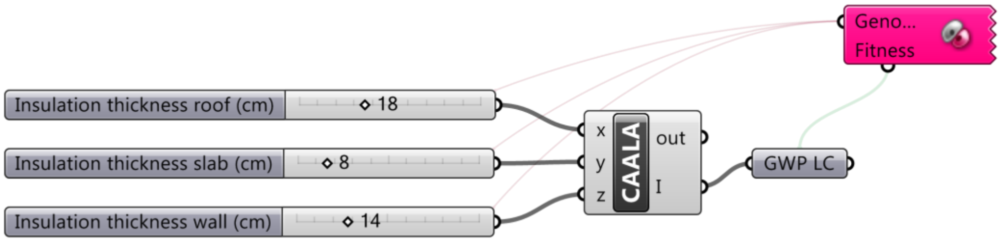

Figure 29: Example of an optimization set-up using Galapagos

3.2.5. Summary of Section 3.2

Which software implementation is necessary to be able to apply the parametric method?

The implementation of PLCA requires the use of parametric design software. In this thesis, it has been implemented in Grasshopper3D (GH). Both the calculation of energy demand and embodied impact are fully integrated into GH, making exporting and re-importing unnecessary. In this way, the parametric tool called CAALA – Computer-Aided Architectural Life cycle Assessment – developed in this thesis is able to provide the LCA results in real time. GH provides different optimizers, which can be linked to CAALA to minimize the environmental impact of a building design.

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[76] Galapagos is an evolutionary algorithm integrated in Grasshopper and developed by David Rutten

[77] Goat has been developed by Simon Flöry and can be downloaded for free at http://www.rechenraum.com/de/referenzen/goat.html (accessed March 14th 2016)

[78] Octopus is an evolutionary multi-criteria optimization plug-in for Grasshopper3D. It is based on SPEA-2 and HypE optimization algorithms and developed by Robert Vierlinger. The software is available at http://www.food4rhino.com/project/octopus?etx (accessed February 9th 2016)

3.3. Verification of the calculation algorithms

The easiest way to verify the algorithms developed for this thesis would be to verify the results. However, verification of the results provided by PLCA is difficult, because the environmental impact of an existing building cannot be directly measured. As noted in Section 1.2.1.5, the results of an LCA study can only indicate potential environmental impact caused by a product or service. The environmental impacts of a single product throughout its life cycle cannot be studied empirically. Furthermore, environmental impacts that are observed in the world cannot be connected to products by an experimental method. LCA practitioners usually employ predefined LCIA data for the assessment of buildings and rely on the quality of the data provided in databases or EPDs.

Nevertheless, the aim of this section is the verification of the algorithms established in Section 3.1.2. The calculations for operational and embodied impacts are checked separately for correctness. A reference building is calculated for the verification and the results provided by CAALA are compared to those of a study by Hartwig (2012). These have been calculated using Excel spreadsheets according to DGNB guidelines. The reference building is called *Woodcube* and the main structure consists of wood, which is not typical for residential buildings in Europe. Therefore, a modified reference building based on the original called *Concretecube* is established. The two buildings possess the same geometry and same function, but differ in the main building materials.

This section is divided into three parts. The first part describes the modelling of the reference buildings and explains the modifications made for the purpose of verification. The second part compares the operational impact results and the third part compares the results for embodied impact.

3.3.1. Reference buildings

The Woodcube is a five-storey residential building in Hamburg and was built as part of the International Building Exhibition (*Internationale Bauausstellung*) 2013. The building measures approximately 15 × 15 m and possesses a core consisting of a staircase and an elevator. Eight apartments with a total NGA of 1024 m² are arranged around this core (see Figure 30 and Figure 31).

Figure 30: Woodcube, floor plan, ground floor (Hartwig 2012, p.50)

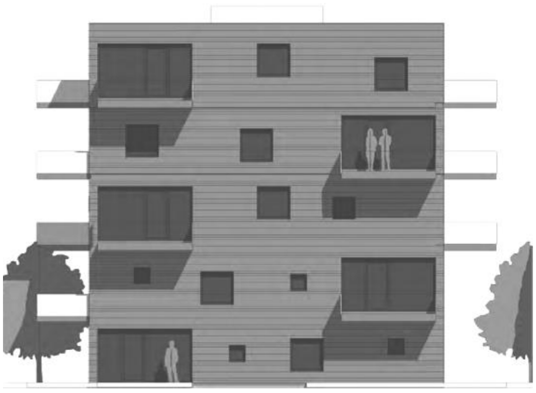

Figure 31: Woodcube, south elevation (Hartwig 2012, p.58)

3.3.1.1. Geometry input

The Woodcube's geometry was modelled in Rhinoceros based on the plans and sections provided in the study by Hartwig (2012, pp.49-61). The floor plans were imported into Rhinoceros and extruded to generate the 3D model consisting of surfaces (see Figure 32). The floor plans are from the design stage, and in some cases the dimensions differ from those provided in the sections and views which made some assumptions necessary.

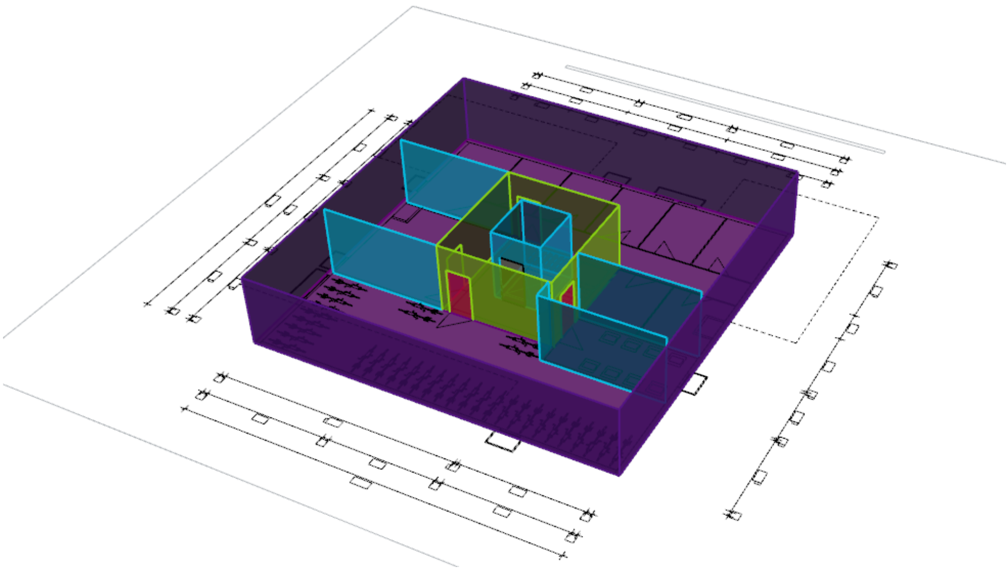

Figure 32: Import of floor plans and extrusion for surfaces in Rhinoceros

The building was modelled in two steps. First, all components of the building envelope which form part of the boundary between conditioned zone (living space) and unconditioned zone (unheated basement and exterior) were added to build the thermal model (see Figure 33). This thermal model was used for calculation of the operational energy demand and the resulting environmental impact. In the second step, all remaining building components were added (see Figure 34). The combined model, consisting of Figure 33 and Figure 34, was used to calculate the embodied impact.

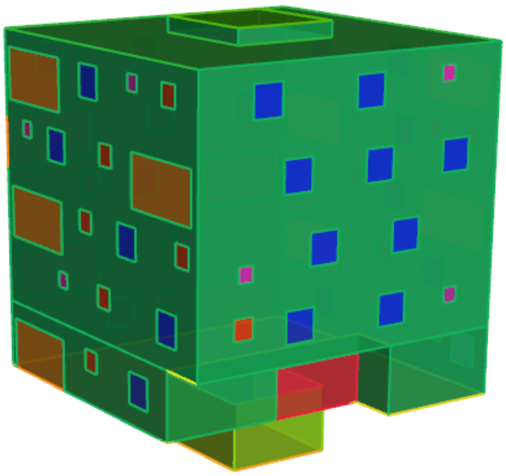

Figure 33: Thermal model

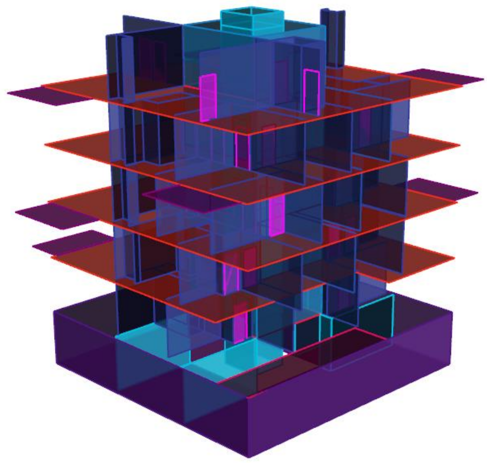

Figure 34: Additional surfaces

3.3.1.2. Material input for Woodcube

To input the building materials, a building component catalogue was established from the materials provided in the study, which was then imported into CAALA. This component catalogue includes the necessary physical properties for the energy demand calculation, as well as environmental and RSL data needed for the embodied impact calculation. The following adaptations to the building components catalogue from Hartwig's study were made for the calculation:

- Elevator, heating system, and piling foundation were not modelled geometrically and left out of the calculation.
- In the study, the wooden cladding of the *basement ceiling with parquet floor* is described with a RSL of 5 years only. However, it possesses an RSL of 50 years in other components, e.g. *basement ceiling bathroom*. Therefore, this was assumed to be a mistake and corrected.
- The component *floor to exterior* is missing in the study. It was added and assumed to have the same set-up as the *wooden ceiling*, but with additional wood fibre insulation
- Components which are described by the number of pieces in the study, e.g. windows and doors, were transformed into area-based input. The value per piece was divided by the size of the component in order to determine the value per m².

3.3.1.3. Material input for Concretecube

The Concretecube possesses the same geometry as the Woodcube, but some wooden components have been modified. The wooden exterior wall was exchanged for a wall made of reinforced concrete and EPS (see Table 30), which possesses the same u-value. Therefore, it can be assumed that the energy demand of the Woodcube and Concretecube are equal. The wooden ceilings were exchanged for concrete ceilings which are similar to the concrete basement ceiling of the original study. The only difference is that the insulation layer was left out, because it is not needed within the thermal zone (see Table 31).

Table 30: Modified concrete exterior wall

Layer	Material	Thickness
1	Cement plaster	20 mm
2	EPS 035	180 mm
3	Reinforced concrete C20/25 (2% reinforcement)	180 mm
4	Gypsum plaster	20 mm

Table 31: Modified concrete ceiling with parquet floor / tiles for bathrooms

Layer	Material	Thickness
1	Wooden floor / Tiles	(not provided in the study)
2	Dry screed	20 mm
3	Foil	1 mm
4	Dry screed	20 mm
5	Impact sound insulation	30mm
6	Filling	60 mm
7	Foil	1 mm
8	Reinforced concrete C20/25 (2% reinforcement)	190 mm
9	Wood cladding	20 mm

The environmental data for the concrete exterior wall was taken from eLCA. For the concrete ceilings, the environmental data provided in the study from Hartwig was employed. The environmental data for each component is provided in Table 32. The detailed list of data for each material can be found in Appendix C.

Table 32: Environmental data for components replaced with concrete equivalents

	GWP [kg CO_2-e/m²]	ODP [kg R11-e/m²]	POCP [kg C_2H_4-e/m²]	AP [kg SO_2-e/m²]	EP [kg PO_4^{3-}-e/m²]	PENRT [MJ/m²]	PERT [MJ/m²]
Concrete exterior wall	122.41	3.8258E-06	0.0339	0.2477	0.0339	1483.51	50.49
Concrete ceiling with parquet floor	75.59	4.407E-06	0.0314	0.2783	0.0379	1104.45	1095.58
Concrete ceiling bathroom	107.01	3.8059E-06	0.0283	0.2554	0.0330	1062.57	595.63

3.3.2. Operational impact

This section on the verification of the operational impact consists of three parts. In the first part, the areas of the modelled geometry are compared to the areas in the study. The second part focusses on the comparisons of the energy demand. Finally, the differences in the results of the operational impacts are considered.

3.3.2.1. Comparison of areas

The areas of the building components forming the thermal model needed for the energy demand calculation are shown in Table 33. The overall area difference is 16.77 m², which amounts to a deviation of 1.14%. The differences for some individual components are higher. Considering that the plans used as a reference for modelling the geometry were from the design phase, the overall discrepancy is low.

Table 33: Differences in areas in thermal model

	Name CAALA	Name Hartwig	Hartwig [m²]	CAALA [m²]	Difference [m²]	Deviation [%]
Walls	Wall to exterior 1 North	AwNord	213.24	201.13	12.11	5.68
	Wall to exterior 1 East	AwOst	179.88	174.79	5.10	2.83
	Wall to exterior 1 South	AwSüd	170.72	165.00	5.72	3.35
	Wall to exterior 1 West	AwWest	178.12	172.67	5.45	3.06
	Wall to exterior 2 North	AwTRH Ü N	5.01	3.36	1.65	32.91
	Wall to exterior 2 East	AwTRH Ü O	5.01	3.67	1.34	26.84
	Wall to exterior 2 South	AwTRH Ü S	5.01	3.36	1.65	32.91
	Wall to exterior 2 West	AwTRH W	5.01	3.67	1.34	26.84
	Basement wall to unheated basement	IwKeller	52.78	52.73	0.05	0.09
Windows and doors	Window 1-4 North	Fenster Nord	20.27	20.01	0.26	1.27
	Window 1-4 East	Fenster O	53.63	56.25	-2.61	-4.88
	Window 1-4 South	Fenster S	62.78	66.03	-3.25	-5.18
	Window 1-4 West	Fenster W	55.38	58.36	-2.98	-5.38
	Door to unheated basement	Iw Keller	8.00	8.09	-0.09	-1.17
	Door to exterior 1	F AwN	5.84	5.24	0.60	10.34
	Door to exterior 2	T AwN	4.62	4.65	-0.03	-0.74
Floor and roof	Roof 1	Dach	202.10	202.87	-0.77	-0.38
	Roof 2	D TRH Ü	24.40	25.14	-0.74	-3.04
	Floor to unheated basement	Kellerdecke zu unbeheiztem KG	178.81	184.15	-5.34	-2.99
	Floor to ground	GF_Treppe	22.49	25.14	-2.65	-11.79
	Floor to exterior	DE01	21.12	21.15	-0.03	-0.15
Sum			**1474.22**	**1457.45**	**16.77**	**1.14**

3.3.2.2. Comparison of energy demand

The operational impact mainly depends on the operational energy demand. In contrast to environmental impacts, the energy use for the operation of the building can easily be measured. In order to verify the energy demand calculation methods, the results can be compared. Usually, large deviations occur, which mainly result from user behaviour (cf. Stolte et al. 2013, p.7). For example, the user may heat and ventilate the building differently than the user profiles provided in the standards. For both methods, QSSM and DBPS, verification of the calculation method has been done for DIN V 18599-2:2011[79] and EnergyPlus[80]. Therefore, it can be assumed that the calculation methods are correct.

For the LCA with CAALA, the DIN V 18599-2:2011 method has been implemented in GH. The operational energy demand calculation in the study is based on DIN 4108-6:2013. While only DIN V 18599-2:2011 is applicable for non-residential buildings, both standards are equally applicable for residential buildings. However, there are significant differences in the calculation methods that they employ (Himburg 2011, p.3). This makes the comparison of operational energy demand results provided by the GH tool with those of the study questionable.

The implementation of DIN V 18599-2:2011 in GH has already been verified for residential buildings (Lichtenheld et al. 2015, p.3). It has been compared to two different state-of-the-art software tools and showed negligible deviation. Therefore, it is not necessary to verify the implemented algorithms for energy demand calculation again.

3.3.2.3. Comparison of environmental impact

To review the algorithms for the operational impact calculations, the results for the final energy demand provided by Hartwig are input into CAALA. The results of CAALA with these modified energy demand results and the deviation from the original study are shown in Table 34.

Table 34: Differences in operational impact results between the study and CAALA modified

	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3}-e]	PENRT [MJ]	PERT [MJ]
Hartwig	-51,120	-0,00001	1,960	16,310	2,990	-10091	211251
CAALA modified	-51,484	-7,129E-06	1,957	16,309	2,986	-10097	211251
Difference	0,364	-2,871E-06	0,003	0,001	0,004	6	0
Deviation [%]	-0,712	28,71	0,153	0,006	0,134	-0,059	0

[79] See http://www.18599siegel.de/qualitaetssicherung/ (accessed March 12th 2016)

[80] See https://energyplus.net/testing (accessed March 12th 2016)

The differences between CAALA and the study by Hartwig are assumed to result from rounding errors. The results in the study are only provided with five decimal places of accuracy, and the deviation is especially high where the indicator results have very low absolute values, for example for ODP, where the deviation is 28.71%. For all other indicators the deviation is under 1%. Therefore, the calculation of operational impact based on the energy demand input is shown to be correct.

3.3.3. Embodied impact

To verify the embodied impact calculation, an audit was performed to confirm that all data was multiplied and summed up correctly and that all materials have been accounted for. The embodied impact results provided by CAALA are compared to the results of the study by Hartwig.

The approach consists of two steps: First, the areas of building components are compared. Second, the results for the environmental impact are compared for Woodcube and for Concretecube.

3.3.3.1. Comparison of areas

Differences in the areas between the study by Hartwig and the geometric model for CAALA are displayed in Table 35. The overall deviation is 6.66%. Large differences can be found in some individual building components. These are explained in the following:

- *Interior wall staircase* and e*xterior wall staircase above roof*: As explained previously, for internal walls the centre line has been used as reference to model the 2D wall surface. In the study by Hartwig, the calculation method for the walls is not explained and the walls might have been calculated differently.
- *Wooden ceiling with parquet floor*: In the study by Hartwig, the exterior part of the ceiling above the entrance cannot be found in the calculation of embodied impact. In the energy demand calculation, it is identified as *floor to exterior*. It has been assumed that this part was missed in the study and it has been added to the model for CAALA.
- *Interior wall*: The modelling of interior walls according to the plans provided in the study has been difficult, because in some parts the indication was not clear. Again, the centre line has been used as reference which might have been calculated differently in the study.

Other discrepancies are assumed to result from inaccuracies in the imported plans provided by the study and differences in modelling the geometry.

Table 35: Comparison of areas for the calculation of embodied impacts

Component		Hartwig [m²]	CAALA [m²]	Difference [m²]	Deviation [%]
Walls	Wooden exterior wall	741.95	713.58	28.37	3.82
	Exterior wall basement	183.01	183.01	0.00	0.00
	Exterior wall staircase above roof	20.04	14.05	5.99	29.88
	Interior wall staircase	208.15	259.87	-51.72	-24.85
	Interior wall staircase basement	52.78	52.73	0.05	0.09
	Interior wall elevator	135.61	137.56	-1.95	-1.44
	Interior wall	498.29	549.62	-51.33	-10.30
	Interior partition wall	93.84	100.71	-6.87	-7.32
	Interior wall basement	52.46	62.91	-10.45	-19.93
Roofs and ceilings	Bottom slab	228.01	228.01	0.00	0.00
	Roof above staircase	24.00	25.14	-1.14	-4.75
	Wooden roof	204.00	202.87	1.13	0.55
	Wooden ceiling with parquet floor	612.67	736.35	-123.68	-20.19
	Wooden ceiling bathroom	55.61	63.71	-8.10	-14.56
	Basement ceiling with parquet floor	121.62	156.21	-34.59	-28.44
	Concrete ceiling staircase	36.36	36.16	0.20	0.56
	Basement ceiling entrance interior	19.90	11.21	8.69	43.68
	Basement ceiling entrance exterior	22.67	21.15	1.52	6.70
	Basement ceiling bathroom	13.82	16.74	-2.92	-21.11
	Wooden balcony	99.69	90.68	9.01	9.04
Windows and doors	Small window	6.37	6.37	0.00	0.00
	Middle window	10.83	10.83	0.00	0.00
	Big window	54.88	54.88	0.00	0.00
	Entrance door	9.89	9.89	0.00	0.00
	Apartment door	18.00	18.21	-0.21	-1.17
	Balcony door	119.60	128.57	-8.97	-7.50
	Basement interior door	8.00	8.09	-0.09	-1.17
	Interior door	55.80	55.80	0.00	0.00
Sum		**3707.85**	**3954.93**	**-247.08**	**-6.66**

3.3.3.2. Comparison of environmental impact

A summary of the deviations in the CAALA results from Hartwig's study of embodied impact for each indicator is given in Table 36. Tables with the detailed comparison of results for every building component are provided in appendix D.

The greatest differences in the results and the greatest relative deviation of 18.91% can be found for the indicator GWP. This can be explained by the large differences in areas of the concrete wall of the staircase. Compared to the wood employed in most components of the Woodcube, concrete has a high GWP and PENRT. The GWP of wooden components is negative and compensates for the GWP of other components, which led to a negative result for the whole building. The additional GWP of the concrete wall of the staircase significantly lowers the absolute value of the negative GWP, leading to a high relative deviation. At 15.91%, the PENRT deviation is also relatively high. In contrast, deviations for the other indicators range between approximately 6% and 7.6%, and are close to the deviation in areas of 6.6%.

Table 36: Differences in embodied impact results between Hartwig and CAALA for Woodcube

	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3}-e]	PENRT [MJ]	PERT [MJ]
Hartwig	-12082	1.23E-02	82.265	652.809	106.791	865644	7452599
CAALA	-9797	1.31E-02	87.455	702.163	114.549	1003378	7896264
Difference	-2284.55	-8.56E-04	-5.19	-49.36	-7.76	-137733.87	-443677.86
Deviation [%]	18.91	-6.99	-6.31	-7.56	-7.26	-15.91	-5.95

The comparison of results for the Concretecube in Table 37 shows that the deviations for the different indicators only vary between around 6% and 7.5%, which is very close to the deviation in areas of 6.6%.

Table 37: Differences in embodied impact results between Hartwig and CAALA for Concretecube

	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3}-e]	PENRT [MJ]	PERT [MJ]
Hartwig	261388	1.35E-02	100.531	797.079	111.325	3113212	2792879
CAALA	279897	1.45E-02	106.527	857.055	119.314	3344380	2981113
Difference	-18509.47	-1.01E-03	-6.00	-59.98	-7.99	-231167.71	-188234.23
Deviation [%]	-7.08	-7.51	-5.96	-7.52	-7.18	-7.43	-6.74

In order to account for differences in the environmental impacts resulting from differences in areas between the two models, the area values from Hartwig were input into CAALA. The automatic calculation of areas based on the geometric model was exchanged for the numerically input areas from Hartwig and the results were re-calculated. The summary of results for the Woodcube is shown in Table 38 and the complete table with all results can be found in Appendix D. The relative deviation is smaller than 0.01 % for all indicators. The minor differences may result from rounding errors.

Table 38: Differences in embodied impact results between Hartwig and CAALA modified for Woodcube

	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3}-e]	PENRT [MJ]	PERT [MJ]
Hartwig	-12082	1.23E-02	82.265	652.809	106.791	865644	7452599
CAALA modified	-12082	1.23E-02	82.267	652.807	106.791	865644	7452586
Difference	0.126	1.70E-06	-0.002	0.002	0.000	-0.053	13.126
Deviation [%]	-0.001	0.014	-0.003	0.000	0.000	0.000	0.000

The results for the Concretecube are shown in Table 39. The relative deviation also smaller than 0.01 % for all indicators.

Table 39: Differences in embodied impact results between Hartwig and CAALA modified for Concretecube

	GWP [kg CO_2-e]	ODP [kg R11-e]	POCP [kg C_2H_4-e]	AP [kg SO_2-e]	EP [kg PO_4^{3}-e]	PENRT [MJ]	PERT [MJ]
Hartwig	261388	1.35E-02	100.531	797.079	111.325	3113212	2792879
CAALA modified	261388	1.35E-02	100.533	797.078	111.326	3113223	2792879
Difference	-0.002	1.03E-06	-0.002	0.001	-0.001	-10.464	-0.129
Deviation [%]	0.000	0.008	-0.002	0.000	-0.001	0.000	0.000

The deviations between the results of Hartwig and CAALA modified prove to be very little and can easily be neglected. As such, CAALA's results for embodied energy have been shown to be correct.

3.3.4. Summary of Section 3.3

Does the parametric method provide the same results as a reference study?

The verification of the results obtained using PLCA is difficult, because the environmental impact of an existing building cannot be directly measured and compared to the results. LCA practitioners assessing buildings need to rely on the quality of the data provided in data-bases or EPDs. To verify the algorithms established in this thesis, the results provided by CAALA were compared to those of a reference building in a study published by Hartwig (2012). The calculations of operational and embodied impact were verified separately. The energy demand values provided by the study were input into CAALA and the operational impact was calculated. The resulting deviation is smaller than 0.01%. For verification of the embodied impact, the areas of the individual building components provided by the study were input in CAALA. The deviation between the results of the study and CAALA is also smaller than 0.01%. It can be assumed that this small deviation results from rounding errors. As such, the algorithms developed for this thesis provide the same results and are understood to be correct.

3.4. Summary of Chapter 3

What are the main characteristics of the parametric method?

The key element of the method called *Parametric Life Cycle Assessment* (PLCA) is a digital, *parametric LCA model*. The workflow for using the model can be divided into four steps: input, calculation, output, and optimization. The unique and most important characteristic of the model is that all four steps and all components within those steps are interlinked and form a closed calculation loop. This provides the basis for optimization.

The basic prerequisite for the parametric model is the parametrization of all input. The input consists of *geometry*, *building materials and services*, and *determining factors*. The geometry is input via a 3D model which is parametrized or directly defined parametrically. A combined database for building materials and services containing all necessary data is established and linked to the model. The determining factors are also defined parametrically. The energy demand calculation is implemented within the calculation step to avoid the exporting and importing necessary for conventional approaches. Based on the algorithms developed, the whole life cycle impact is calculated and output. Various possibilities for visualization of the LCA results are provided. Using this self-contained workflow, the architect can quickly generate variants manually to iteratively improve a building design or employ computational optimizers.

4. Evaluation of the parametric method

The aim of this chapter is to evaluate the applicability of PLCA for environmental building design optimization using hypothetical case studies. Furthermore, PLCA will be assessed to confirm whether it fulfils the requirements established in Chapter 2. Chapter 4 consists of four main sections. In each of the first three sections, PLCA is employed in a different scenario to cover a range of possible applications for design optimization. Nevertheless, further possibilities for application exist, and besides design optimization, PLCA could be used for scientific studies not covered in this thesis, e.g. to analyse the influence of certain building components on the LCA results. In section four, PLCA is evaluated using the checklist provided in Section 2.5. Furthermore, the time-efficiency of the method is discussed.

The examples in the first three sections are structured according to the objective of the optimization. The first case study focussed on the optimization of building materials for the refurbishment of a detached single-family house where the geometry remains unaltered. In the second example, PLCA was applied for the geometric optimization of a new residential building design. Various design variants for the building's geometry were evaluated and compared in the conceptual design stage in order to find the most promising geometry for further planning. The third case study describes the application of PLCA for both geometric and building material optimization through manual variant comparison as part of a student design project. Furthermore, the purpose of this example was to test the application of the method by non-experts in LCA and the application in a different climate. An overview of the particularities of the three examples is provided in Table 40.

Table 40: Overview of examples of application

Example	Building material optimization	Geometry optimization	Combined geometry and material improvement
Building type	Residential, single family	Residential, multi-family	Mixed use
Design task	Refurbishment	New design	New design
Design stages	3-4	1-2	1-3
Location	Potsdam, Germany	Potsdam, Germany	Mersin, Turkey
Calculation method	QSSM and DBPS	QSSM	DBPS
Calculated energy demand	Heating	Heating	Heating and cooling
RSP	30 years	50 years	50 years
LCA type	Simplified LCA	Screening LCA	Simplified LCA
Optimization approach	Computational	Semi-automated	Manual
Publications	Hollberg & Ruth (2013); Hollberg & Ruth (2014); Klüber, Hollberg, et al. (2014); Hollberg & Ruth (2016)	Hollberg, Klüber, et al. (2016)	Hollberg, Ebert, et al. (2016)

The case studies have been partly published in different contexts. Here, each case study is structured similarly to a scientific paper and the results are briefly discussed within each study. The individual results of the case studies are not of primary interest, but the examples of application serve to evaluate the method in Section 4.4 according to the requirements established in Chapter 2.

4.1. Building material optimization

In this example, PLCA was used to find the environmentally optimal solution for the refurbishment of a detached single-family house. Computational optimizers were employed to find the optimum combination of insulation material and insulation thickness considering various options for building services. This example has been used for different case studies with different focusses, published in Hollberg & Ruth (2013); Hollberg & Ruth (2014); Klüber, Hollberg et al. (2014) and Hollberg & Ruth (2016). Here, an overview is given and the results presented in Hollberg & Ruth (2016) are summarized.

4.1.1. Objective

The number of single and two family houses in Germany built before the first Thermal Insulation Ordinance in 1977 is around 10 million (Bigalke et al. 2012, p.25). In most cases, these houses are not insulated, and they account for approximately 75% of the total final energy demand for space heating and hot water in the building sector (Bigalke et al. 2012, p.28). For the years 2005-2008, the rate of refurbishment was around 0.8% per annum (Diefenbach et al. 2010, p.71), but the aim of the German government is to raise this rate to 2% per annum (BMWi 2010, p.22). This indicates a high demand for energy efficient refurbishment in the near future.

When renovating a building many questions arise, including which measures are most beneficial, and where to start. In particular, the question as to whether external insulation should be applied is heavily discussed (see Molter & Linnemann (2010, pp.26–49) or Jelle (2011, p.2562), for example), and the optimum insulation thickness has been the focus of many scientific studies, e.g. Hasan (1999, pp.119-123), Çomaklı & Yüksel (2003, pp.476-479), Dombaycı (2007, p.3858), and Ozel (2011, pp.3858-3862).

In this case, finding the optimum insulation thickness means finding the trade-off between operational impact (I_O) and embodied impact (I_E). Increasing the insulation thickness causes a reduction in I_O and a rise in I_E. With increasing thickness, the U-value of the building envelope converges asymptotically towards zero. Thus, each additional centimetre of insulation contributes less to reducing transmission heat loss than the previous one. Consequently, there is an ‘environmental break-even point’, as shown in Figure 35. It is then no longer worthwhile to add further insulation because the added I_E cannot be amortized within the assessment period.

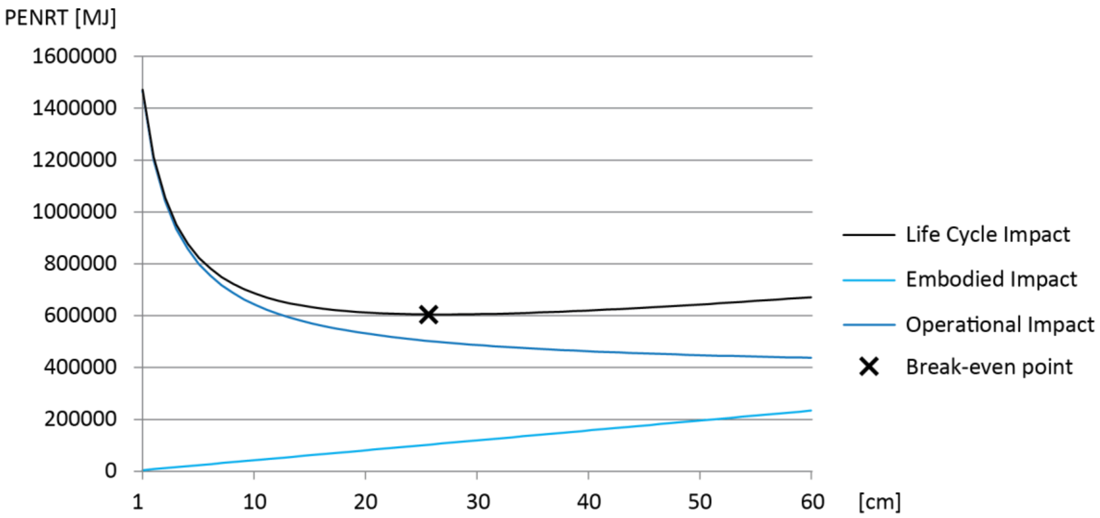

Figure 35: Break-even point of added insulation

The objective of this study was to find the insulation material and insulation thickness with minimum life cycle environmental impact (I_{LC}) to refurbish a single-family house, considering various options for building services, and the specific boundary conditions of the building. Two scenarios were investigated:

A. All components of the thermal envelope are insulated with the same thickness;

B. The individual components of the thermal envelope are insulated with different thicknesses.

Furthermore, whether the original windows should be replaced was also considered.

4.1.2. Method

In this part, the procedure for conducting the LCA using PLCA is explained and the workflow consisting of input, calculation, output, and optimization is described.

4.1.2.1. Input

Geometric information

The reference building is a typical single-family house in Potsdam, Germany from the 1960s (see Figure 36 and Figure 37). The geometry was drawn in Rhinoceros (see Figure 38) and imported into GH. Since the existing building materials were not assessed, only the thermal envelope to be refurbished with insulation was modelled. The building had a heated attic storey under the roof, but the upper part of the roof was not heated. As such, the thermal envelope consisted of four components – exterior wall (including windows), uppermost ceiling, roof, and floor slab. An entry door was neglected here for simplification.

Figure 36: View from garden (IfLB 1987, p.50)

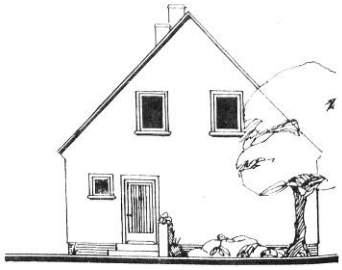

Figure 37: View from street (IfLB 1987, p.50)

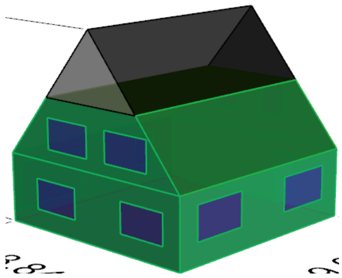

Figure 38: Geometry modelled in Rhino

Building materials and services

It was assumed that the existing building was made of bricks without insulation. Detailed information on the physical properties of the existing building components can be found in Appendix E.

To define possible refurbishment solutions, nine different insulation materials common for refurbishment in Germany were chosen which are common. It was assumed that these materials could be varied in thickness from 0 to 60 cm in steps of 1 cm.

- Expanded Polystyrene (EPS)
- Extruded Polystyrene (XPS)
- Polyurethane foam (PUR)
- Glass wool (GW)
- Stone wool (SW)
- Foam glass (FG)
- Wood fibre insulation boards (WFIB)
- Cellulose insulation boards (CIB)
- Vacuum insulation panels (VIP)

Additionally, the option of replacing the windows was included. The original windows could be exchanged for either double or triple-glazed windows with a PVC frame.

- Original windows (O)
- Double glazing, PVC frame (D)
- Triple glazing, PVC frame (T)

To take different possible heating systems into account, seven different heating systems were defined. However, the I_E of the heating systems was not considered. The first was a conventional gas-fired condensing boiler with an estimated efficiency of 98%. The current alternative for boilers is a heat pump (HP), which uses a heat source to transfer heat to a destination. The efficiency mainly depends on the temperature difference between the source and the destination. Here, the efficiency throughout the year is described as a performance factor (PF). The following PFs were assumed: 3.5, 4.8, and 7.0. The latter can be achieved when used in combination with thermal energy storage, for example. HPs can be fuelled by either gas or electricity. Two scenarios for electricity were chosen: the electricity mix in Germany, and renewable energy provided by wind turbines in Germany. Wind was chosen because it provides the greatest contribution to the mix of electricity provided by renewable sources in Germany (IWES 2012, p.9). Wind energy fluctuates considerably, but the availability is higher in winter (IWES 2012, p.19) when heating is needed, and solar energy is scarce in northern countries such as Germany. Combining the two electricity mixes with the three PFs of the heat pumps and the gas-fired condensing boiler resulted in seven possible heating systems:

- Gas-fired condensing boiler with a PF of 0.98 (G)
- Heat pump with a PF of 3.5 fuelled by electricity mix (H1m)
- Heat pump with a PF of 4.8 fuelled by electricity mix (H2m)
- Heat pump with a PF of 7.0 fuelled by electricity mix (H3m)
- Heat pump with a PF of 3.5 fuelled by electricity from wind turbines (H1w)
- Heat pump with a PF of 4.8 fuelled by electricity from wind turbines (H2w)
- Heat pump with a PF of 7.0 fuelled by electricity from wind turbines (H3w)

The physical data employed is based on DIN 4108-4:2013 and environmental data is based on ökobau.dat. The RSL data were taken from BBSR[81]. The combined data is shown in Appendix E. Eight indicators were employed for evaluation of the refurbishment solutions:

[81] The table with RSL data used for BNB certification system is called *Nutzungsdauern von Bauteilen zur Lebenszyklusanalyse nach BNB* and is provided by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (Bundesinstitut für Bau-, Stadt- und Raumforschung - BBSR). It can be downloaded at http://www.nachhaltigesbauen.de/baustoff-und-gebaeudedaten/nutzungsdauern-von-bauteilen.html (accessed March 12th 2016)

- Primary Energy Total (PET)
- Primary Energy Non-renewable Total (PENRT)
- Global Warming Potential (GWP)
- Ozone Layer Depletion Potential (ODP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Photochemical Oxidation Potential (POCP)
- Abiotic Resource Depletion Potential Element (ADPE)

Determining factors

The RSP was set to 30 years, because the existing building was already 50 years old and 30 years was assumed to be a realistic period for further use. The RSL of all new materials is at least 30 years and the existing material was also assumed to last for this period, which sets the number of replacements to zero. Both climate and user data were taken from DIN V 18599-10:2011 (see Table 41).

Table 41: Determining factors

RSP	30 years
Climate data	DIN V 18599-10:2011, climate region 4 – Potsdam, page 89
User data	DIN V 18599-10:2011, single-family house, page 17

4.1.2.2. Calculation

Operational Impact

When refurbishing residential buildings in Germany, the heating demand is most relevant for operational energy. According to Bigalke et al. (2012, p.14), the energy needed for space heating of residential buildings amounts to 85% of the total operational energy demand. Lighting, appliances, and other consumers of electric energy were not part of the refurbishment in this example and the ventilation occurred naturally. Therefore, only the calculation of heating demand was integrated here. As such, the I_O could be simplified (see Equation 6).

$$I_O = ED_{heat} / PF_{heat} \times IF_{O,heat} \times RSP \tag{6}$$

The tool developed for GH (Lichtenheld et al. 2015, pp.1-3) based on the QSSM of DIN V 18599-2:2011 was used for calculation of the heating demand.

Embodied Impact

For the simplified calculation of I_E, only the building envelope was assessed, because the goal was to determine the optimum insulation material and thickness. It was assumed that the primary construction could be left unchanged. Furthermore, for reasons of simplification, it was assumed that the type of surface covering the insulation was the same for all insulation materials, and it was therefore excluded from consideration in the LCA. The environmental impact of the heating system was not integrated. With these simplifications, the I_E could be reduced to the embodied impact of the insulation material and the windows (see Equation 7).

$$I_E = M_{ins} \times IF_{E,ins} \times (1 + R_{ins}) + M_{win} \times IF_{E,win} \times (1 + R_{win}) \tag{7}$$

4.1.2.3. Output

The results were exported to spreadsheets for further analysis.

4.1.2.4. Optimization

For the computer-based optimization, a plugin for GH called *Goat*[82] was used. Within this plugin, the evolutionary algorithm *CRS2* (Kaelo & Ali 2006, pp.256–263) was employed, which is provided by *NLopt library*[83]. As explained in 1.3.4, the optimizer randomly varies the adjustable parameters (insulation material, insulation thickness, and window type) within given boundaries to find a first generation of possible solutions. These are evaluated according to the objective function (minimum I_{LC}). The best solutions are recombined and form a second generation of possible solutions, which is then re-evaluated. This iterative process is continued until an abort criterion is reached.

[82] Goat has been developed by Simon Flöry and can be downloaded for free at http://www.rechenraum.com/de/referenzen/goat.html (accessed March 14th 2016)

[83] NLopt is an open-source library for nonlinear optimization provided by Steven G. Johnson and can be downloaded at http://ab-initio.mit.edu/wiki/index.php/NLopt (accessed March 14th 2016)

4.1.3. Results

Scenario A

The assumptions for Scenario A – nine different insulation materials ranging from 0 to 60 cm in steps of 1 cm, three possible window types and seven variants of heating systems – resulted in a solution space of 9×61×3×7=11529 possible solutions. To provide a basis for verification of the optimization process, a loop through all the possible solutions was run in a first step. This took about 20 minutes on a standard PC[84]. The solutions were exported to a spreadsheet and sorted according to the minimum impact for each heating system and each indicator. The optimum results for each heating system and all eight indicators are shown in Figure 39.

In the second step, the CRS2 optimizer was employed. The run time limit was set to 6 minutes. The objective function was defined as minimum $PERNT_{LC}$. A comparison of the provided solution with the loop proves that the optimizer found the minimum within the given time limit.

[84] Here, standard PC refers to an Intel i3 processor 2.1 GHz and 8GB RAM.

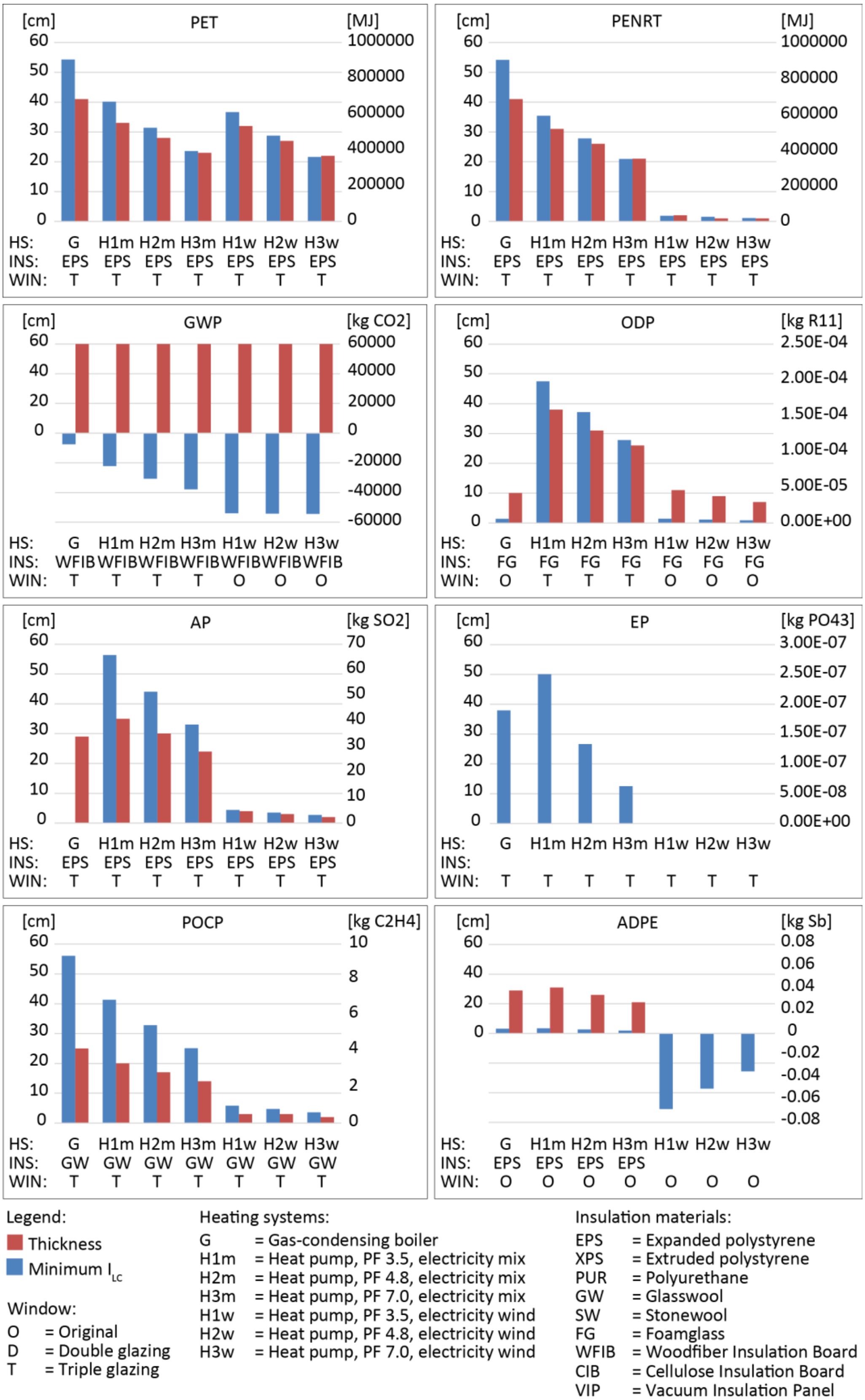

Figure 39: Results for minimum I_{LC} depending on heating system and indicator

Scenario B

In Scenario B, the CRS2 optimizer was applied for an extended study. It was assumed that each of the four building components comprising the thermal envelope could be insulated with a different thickness. For a given heating system – a heat pump fuelled by electricity from the German energy mix with a PF of 4.8 (H2m) – this resulted in a search space of $9 \times 61^4 \times 3 = 373.8$ million possible solutions. For this extended search space, the time limit for the optimizer was set to 15 minutes. The result for minimum $PERNT_{LC}$ found by the optimizer is 462243 MJ and the optimum combination is displayed in Table 42.

Table 42: Combination for minimum $PENRT_{LC}$

Component	Material	Thickness [cm]
Exterior wall	EPS	26
Uppermost ceiling	EPS	27
Roof	EPS	29
Slab	EPS	23
Window	Triple glazing	

Although the calculation of a single solution took less than 0.1 seconds, the calculation of all solutions would have taken more than 430 days on a standard PC. To verify the solution found by the optimizer by running a loop of all solutions was therefore impractical. Instead, solutions found during the optimization process were plotted and the convergence was analysed. Figure 40 shows that the search space converges strongly after 4000 iterations, which indicates that the optimizer has found a solution close to the optimum. However, it cannot be determined whether the optimizer has found the global optimum within the time limit, or if a local optimum has been identified instead. Figure 40 helps to estimate whether a solution close enough to the optimum has been found. The best solution found within the first 4000 iterations is within 2% of the final solution after 7300 iterations. As such, it can be assumed that further iterations will not significantly reduce the environmental impact.

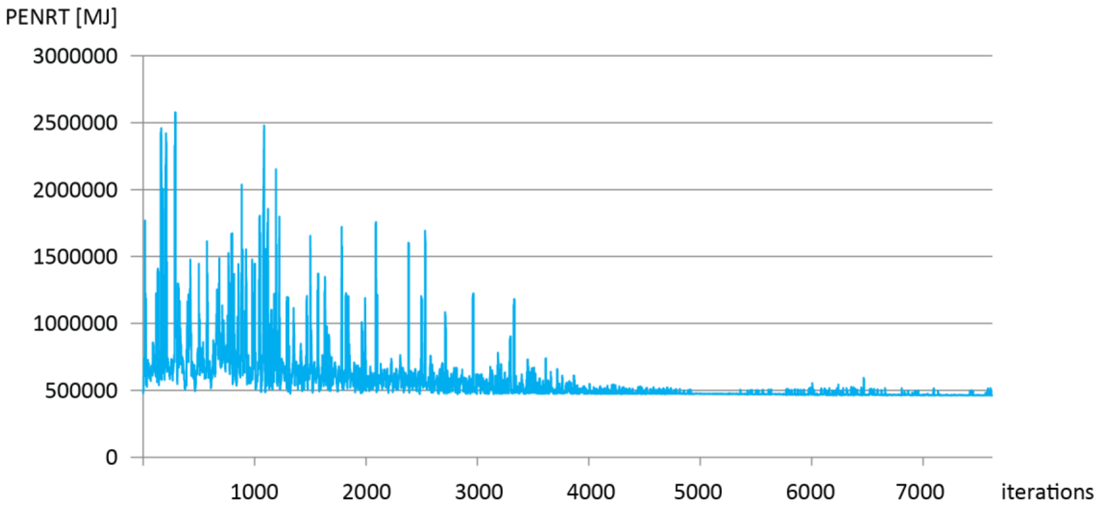

Figure 40: Best combination of insulation material and thickness for PERNT$_{LC}$ and HP 4.8 mix and process of optimization

4.1.4. Discussion

The results illustrated in Figure 39 show the great difference in optimum insulation thickness depending on the heating system and insulation material. For PENRT and PET it is obvious that as the efficiency of the heating system rises, the I_{LC} is lowered significantly. A more efficient heating system leads to less I_O. As a result, the optimum insulation thickness is reduced, leading to less I_E. As noted earlier, the I_E of the heating system was not considered here. The GWP_{LC} also decreases as the efficiency of the heating system increases. The optimum insulation thickness stays constant at 60 cm. 60 cm was chosen as a limit to investigate the theoretical optimum, although this thickness would be impossible in practice. The wood fibre insulation board (WFIB) employed has a negative GWP_E, due to the CO_2 absorbed during the growth of the wood. This leads to an improved result for GWP_E the more material is used. The negative GWP_E even compensates the GWP_O, leading to a negative GWP_{LC}. For the other indicators, the results vary a lot. For example, for EP_{LC} it is best to use no insulation at all, irrespective of the employed heating system.

The optimum window type also varies. For AP_{LC} and EP_{LC} the best results are always achieved with triple glazing in contrast to $ADPE_{LC}$, where the replacement of the original window is not worthwhile. For GWP_{LC} the original window performs better when using electricity provided by wind as the energy carrier, but when using the electricity mix or gas the triple glazing should be employed. For ODP_{LC}, employing triple glazing is only worthwhile when using the electricity mix, while for gas and electricity provided by wind the original window performs better.

Without entering into a detailed discussion of all the indicators, the results clearly show the importance of considering boundary conditions, such as the heating system in this case. These boundary conditions can be easily integrated as defining parameters in PLCA.

The results also show the great divergence among the different indicators. Here, the recommendations of ISO 14044:2006 have been followed and eight indicators have been evaluated in parallel. However, the decision for a 'most environmental friendly' solution based on eight different results is difficult. For communicating the results to architects or their clients a single-score indicator would be more helpful. An example of the application of a single score based on the weighting of DGNB is provided in the next case study.

In earlier publications of similar examples (see Hollberg & Ruth 2014; Klüber, Hollberg et al. 2014), DBPS has been employed to simulate the energy demand. The optimization process took about 3 hours, because each run of the EnergyPlus simulation took 10 seconds. The approach shown here found the minimum environmental impact in Scenario A within a time frame of 6 minutes, which demonstrates the great advantage of QSSM based on DIN V 18599-2:2011. DBPS may still be necessary for office buildings with more complex building services or for determining cooling demand in other climate zones, but for the calculation of environmental impact for residential buildings in Western Europe, QSSM is sufficient.

4.1.5. Supplementary example of multi-criteria optimization

This example shows the application of PLCA for multi-criteria optimization for the refurbishment of the single-family house described previously. The results presented here have partly been published in Klüber, Hollberg et al. (2014).

Objective

As described in Section 1.1, this thesis focusses on environmental sustainability. However, in every building project, costs are an important criterion for decision-making. Therefore, the optimization of a refurbishment measure for investment costs ($Cost_{INV}$) and life cycle global warming potential (GWP_{LC}) is discussed here. The aim of this example was to analyse the cost-efficiency of different refurbishment variants in order to reduce the GWP_{LC} of an existing building. A Pareto front was used to provide a basis for choosing a single variant.

Method

Some assumptions made here differ from the ones described in the previous example. Here, the additional construction required to apply the insulation was also considered, e.g. the substructure of a ventilated façade, and 19 refurbishment variants were analysed, each with a variable insulation thickness between 0 and 70 cm in steps of 2 cm. In this example, data for embodied global warming potential (GWP_E) from the Swiss KBOB[85] was used. In addition, costs were integrated into the combined dataset. The values can be found in Table 86 and Table 87 of Appendix E.

Here, DBPS was used for the calculation of the operational energy. *EnergyPlus* was used as a simulation engine, which was connected to GH with a plug-in called *Archsim*[86].

For the multi-criteria optimization, a plugin for GH called *Octopus*[87] was used, which provides a visualization of the Pareto front during the optimization process. The objective function was minimization of GWP_{LC} and $Costs_{INV}$.

Results

The Pareto front for GWP_{LC} and $Costs_{INV}$ is displayed in Figure 41. The variants on the solutions are Pareto optimal, as they cannot be improved for one criterion without negative consequences for the other criterion.

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[85] The dataset Ökobilanzdaten im Baubereich can be downloaded at http://www.eco-bau.ch/resources /uploads/Oekobilanzdaten/kbob-Oekobilanzdaten-Empfehlung_29_07_2014.pdf (accessed March 12th 2016)

[86] ArchSim is a plug-in to link EnergyPlus with Grasshopper3D. It is developed by Timur Dogan and can be downloaded from http://archsim.com/downloads/ (accessed February 9th 2016)

[87] Octopus is an evolutionary multi-criteria optimization plug-in for Grasshopper3D. It is based on SPEA-2 and HypE optimization algorithms from ETH Zürich and developed by Robert Vierlinger in cooperation with Christoph Zimmel and Bollinger+Grohmann Engineers. The software is available at http://www.food4rhino.com/project /octopus?etx (accessed February 9th 2016)

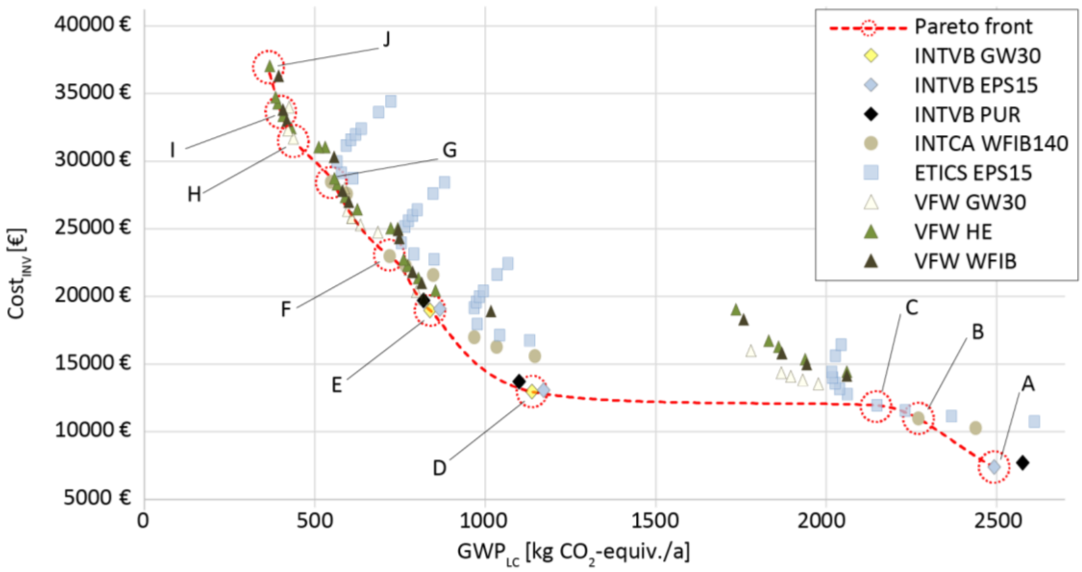

Figure 41: Pareto front for GWP_{LC} and $Cost_{INV}$ (based on Klüber et al. 2014, p.6)

Discussion

Many points on the Pareto front are variants with interior insulation (Points A, B, D, E, F, and G in Figure 41). As such, the results indicate that interior insulation (independent of the insulation material) is a very cost-efficient means of refurbishment. However, it should be pointed out that interior insulation is subject to heavy restrictions and needs an in-depth analysis of the hygrothermal behaviour of the existing wall to avoid condensation. In addition to interior insulation, exterior thermal insulation composite systems (ETICS) are indicated to be Pareto optimal for a low-cost refurbishment (Point C). In order to achieve a large reduction in GWP_{LC}, only a ventilated façade with wood substructure and wood cladding shows Pareto optimality. For this type of construction, glass wool involves lower investment costs (Point H), but in order to achieve very large GWP reductions, renewable raw materials need to be employed for the insulation material - in this case hemp and wood fibre (Points I and J).

Besides this scientific comparison of refurbishment variants, architects can use the visualization of the Pareto front for communication with the client. The Pareto front can help the client to make an informed decision. In this example, the inclination of the Pareto front is very small between Points C and D. When choosing Variant C, the client can reduce the annual GWP to 2150 kg CO_2-e for an investment of 12000 €. When investing 13000 € for Variant D, the annual GWP can be reduced to 1130 kg CO_2-e. This indicates a GWP improvement of 47% for 1000 €, which corresponds to an 8% increase in costs. With this knowledge, the client might want to choose the more environmentally friendly solution. In addition, this can motivate building owners to decide for refurbishment and raise the refurbishment rate, as desired by the German government.

4.1.6. Summary for Section 4.1

Is the method applicable for building material optimization, and which benefits does it provide?

The example of refurbishing a single-family house provides a typical task for building material optimization. It was assumed that the building envelope should be refurbished with additional insulation. The design task was to find the optimum combination of insulation material and insulation thickness for different boundary conditions, such as possible heating systems. A computational optimization approach was chosen to analyse a search space of more than 300 million possible solutions. The evolutionary algorithms employed found the optimum within 15 minutes. This shows that the parametric approach can easily analyse such a great number of variants, which is impossible using conventional approaches, especially within such a short time frame. Furthermore, the results indicate the importance of considering boundary conditions, such as the heating system, and demonstrate that the parametric approach is applicable for building material optimization.

The supplementary example shows that PLCA is also applicable for multi-criteria optimization. The resulting Pareto front of minimum GWP_{LC} and minimum investment costs can be a valuable basis for decision-making.

4.2. Geometric optimization

The aim of this example was to use PLCA to evaluate different geometric variants in the conceptual design stage in order to help the architect decide which geometry to choose for further planning stages. The results for this example have partially been published in Hollberg, Klüber et al. (2016).

4.2.1. Objective

Usually, the architectural design process begins with developing geometric variants for the building shape and finally defining the geometry of the building. LCA results would be valuable to provide a basis for choosing between geometric variants. To provide a single score for the evaluation of geometric variants, a measure for the environmental performance was introduced, which is referred to as life cycle performance (LCP). The aim was to evaluate the potential life cycle performance (PLCP) of different geometric variants in the conceptual design stage in order to help the architect decide which geometry to choose for further planning stages.

4.2.2. Method

Ideally, a multi-stage design space exploration would be carried out to find the solution with the highest LCP. This would lead to a decision tree as described in Section 1.3.4. However, since it is labour-intensive, this is difficult to accomplish in practice. An immense number of combinations are possible. Thus, parts of this process need to be automated, because an architect is not able to manually generate and evaluate all variants. Therefore, the process of creating variants for building materials and heating systems was simulated based on typical choices. The LCP was calculated for all possible resulting combinations. The range of LCP a building geometry achieves was used to characterize the PLCP.

4.2.2.1. Input

Geometric information

The building to be designed should provide eight apartments with a gross floor area (GFA) of 150 m² each. Six geometric variants were compared, each representing one typical type of residential building. To cover a wide range of geometries, the variants ranged from detached houses to an apartment tower. It was assumed that the net floor area (NFA) equals 0.8 × GFA. The storey height of all apartments is 3 m, and the buildings do not have basements. The window area was set to 1/8 of the NFA of each storey, which corresponds to the minimum requirement according to German state building regulations (BbgBO 2008, §40). The geometric variants are displayed in Figure 42.

The geometry was modelled in Rhinoceros and then transferred to CAALA. The whole building envelope and load-bearing interior walls were drawn in Rhino. To simplify the input of non-load bearing interior walls, an estimated value of 60 m² for the interior walls was used. This approach is based on the recommendations for Swiss Minergie certification (Minergie 2016, p.5).

Building materials and services

For each geometric variant, six different kinds of heating systems (H) and six combinations of typical building materials (M) were assumed. The combinations are based on the component catalogue described in Section 3.1.1.2, and the components can be found in Appendix F. Furthermore, three different U-values (U) of the thermal building envelope representing different levels of energy standard were used. All variants in the individual categories could be combined with each other, resulting in 648 possible variants in total (see Figure 42).

Furthermore, the following assumptions were made:

- the ventilation occurs naturally;
- all building material variants include a slab made of reinforced concrete and polyurethane insulation;
- the windows consist of a PVC frame with glazing dependent on the standard for the U-value: double glazing for EnEV 2002 (U1) and EnEV 2014 (U2), triple glazing for Passivhaus (U3);
- all components possess a fire resistance of at least F60;
- to simplify the input of interior walls, they are not modelled in the 3D model, but instead input numerically based on a overall average factor of 0.4 m/m^2_{GFA} (see Table 27).

Determining factors

The functional unit is 1 m² net floor area (NFA) for 1 year, and the RSP is 50 years. It was assumed that the buildings are located in a suburban context without shading from neighbouring buildings in Potsdam, Germany. Both climate and user data were taken from DIN V 18599-10:2011 (see Table 43).

Table 43: Determining factors

RSP	50 years
Climate data	DIN V 18599-10:2011, climate region 4 – Potsdam, page 89
User data	DIN V 18599-10:2011, multi-family house, page 17

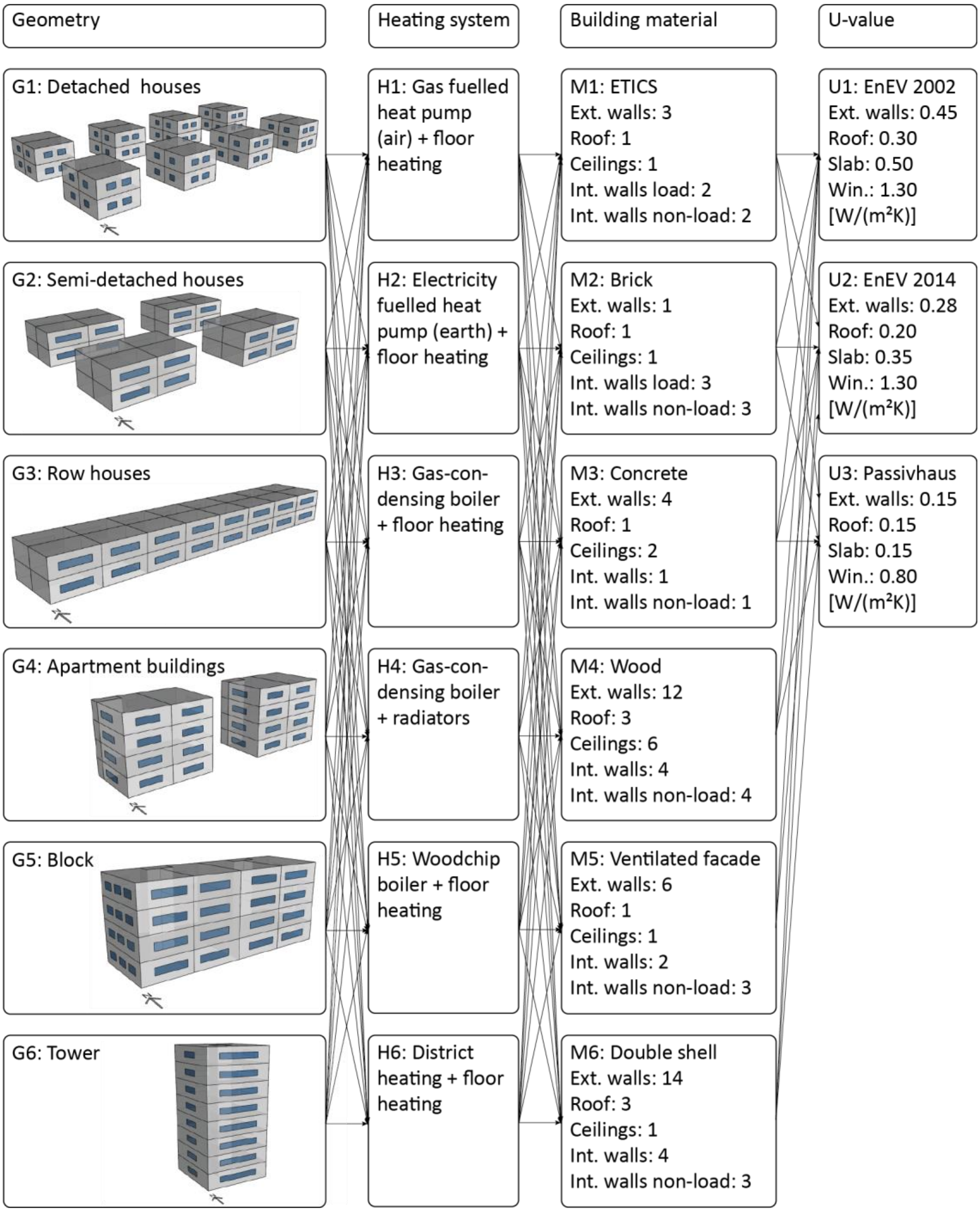

Figure 42: Overview of variants for geometry, heating systems, building material, and U-values

4.2.2.2. Calculation

Operational Impact

Only the energy demand for space heating was calculated using the GH algorithm (Lichtenheld et al. 2015, pp.1–3), based on DIN V 18599-2:2011. Electricity and hot water demand were not calculated, but were integrated using statistical data. The hot water demand was assumed to be 15 kWh/m²a (DIN V 18599-10:2011, p.17), and the electricity demand (final energy) was set at 20 kWh/m²a (BBSR 2011c, p.1).

Embodied Impact

Although this example of LCA as decision support in the conceptual design stage is a screening type, the same level of detail as simplified LCA was chosen. Furthermore, 10% of the results for I_E were added, in order to be in line with the DGNB scoring system.

4.2.2.3. Output

As noted in Section 3.1.3.1, the parametric approach allows an advanced user to define and adjust their own weighting factors in order to consider the individual goals of the LCA study. Furthermore, it allows them to employ different predefined weighting factors, such as those from building certification systems. For the calculation of LCP in this example, the calculation of evaluation points (*Bewertungspunkte*, BP) from the DGNB version 2015 guidelines for residential buildings with more than six apartments[88] was used. A detailed explanation of the procedure for calculating BP, including benchmarks and weighting factors, can be found in Appendix B. A schematic overview is provided in Figure 43.

DGNB employs 44 criteria for evaluating the sustainability of a building, including two criteria based on LCA – ENV1.1 for output-related indicators, and ENV2.1 for input-related indicators. BP are awarded for both criteria.

DGNB provides benchmarks and awards so-called sub-points (*Teilpunkte*, TP) for underscoring these benchmarks. The benchmarks for I_E are fixed for each type of building. The benchmarks for I_O depend on the reference building according to EnEV[89]. The energy demand of this reference building is multiplied by an assumed operational impact factor provided by DGNB. The TP that the building design achieves are weighted by factors (*Gewichtungsfaktoren*, G) and summed up to *checklist points* (CLP). The CLP of both criteria are divided by 10 to provide BP. The BP are weighted according to the influence of the individual criteria ENV1.1 (7.9 percentage points) and ENV2.1 (5.6 percentage points) on the

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[88] The guidelines are not publically available, but they can be requested from DGNB via the association's website: http://www.dgnb.de/en/services/request-dgnb-criteria/form/ (accessed January 17th 2016).

[89] The German energy saving ordinance EnEV uses a reference building to define benchmarks for the energy efficiency of buildings. The reference building is geometrically identical, but has predefined, standardized material properties and determining factors.

overall BP that can be achieved within the certification system. This aggregated value for LCP is called *weighted BP* (WBP) here. A maximum of 1.35 WBP can be achieved. WBP is the single indicator for LCP in this study.

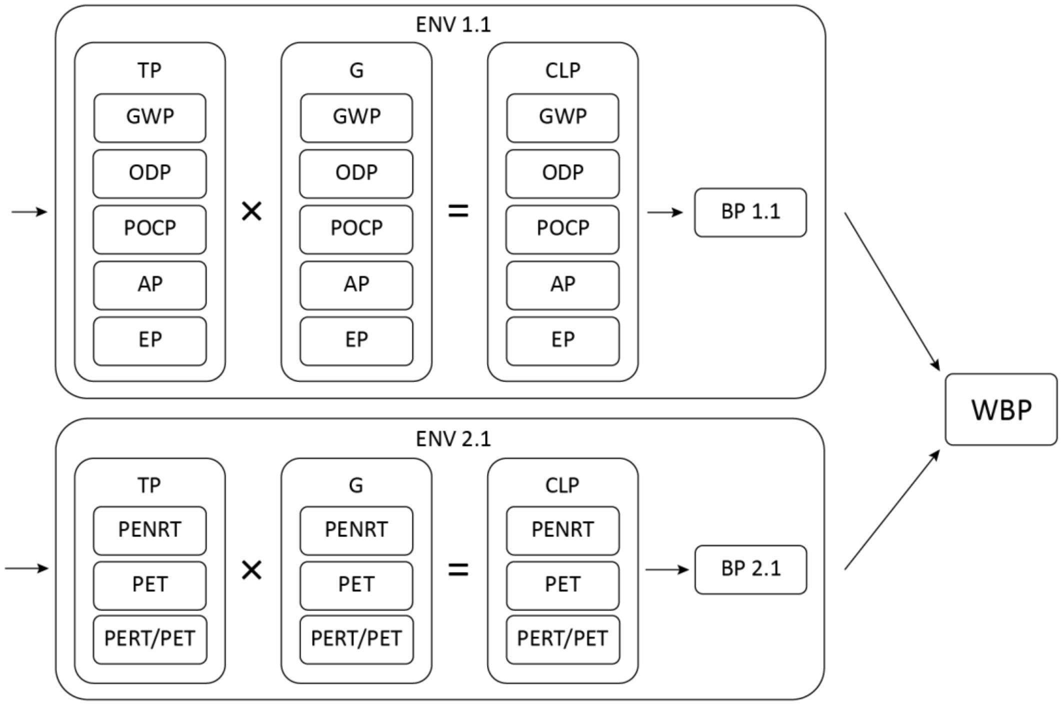

Figure 43: Schematic overview of the weighting process according to DGNB

The results for the midpoint indicators are displayed in a bar chart. The reference values from DGNB served as a benchmark. Additionally, the CLP and the percentage points that can be achieved for the LCA-related criteria are provided (see Figure 44). The output WBP and midpoint indicators were also exported to spreadsheets for further analysis.

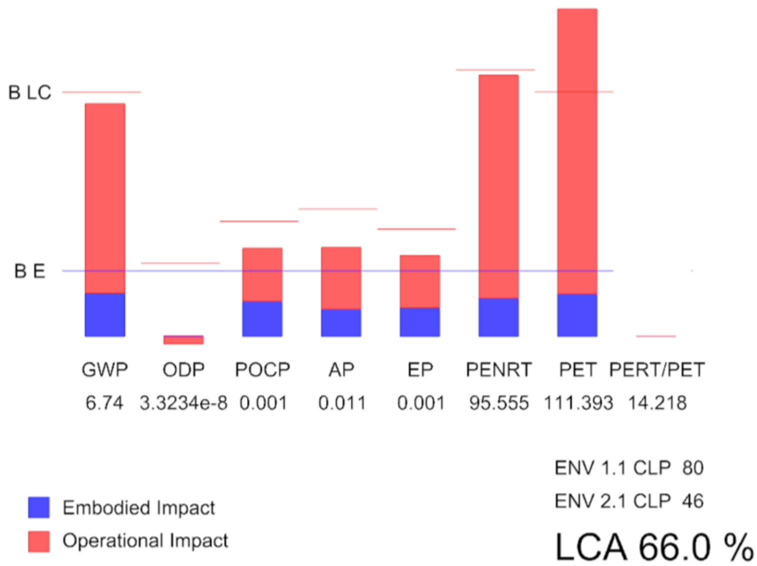

Figure 44: Visualization using a bar chart and the benchmarks of DGNB for normalization

4.2.2.4. Optimization

As noted in Section 4.2.2, a multi-stage design space exploration is labour-intensive and difficult to accomplish in practice. The PLCP approach is not a classical optimization approach, but rather an improvement based on intelligent assumptions. By providing assumptions for choices typically made in design stages 3 and 4, the PLCP allows assessment of the geometries in design stage 2 by predicting the environmental performance.

4.2.3. Results

All 648 possible variants were calculated in a loop. Running a loop of 108 variants per geometry took less than 70 seconds, which illustrates the time-efficiency of the QSSM used for operational energy demand calculation. The WBP achieved by each of the six geometric variants were distributed and normalized to the maximum achievable 1.35 WBP. To visualize the range of results, a boxplot is used (see Figure 45).

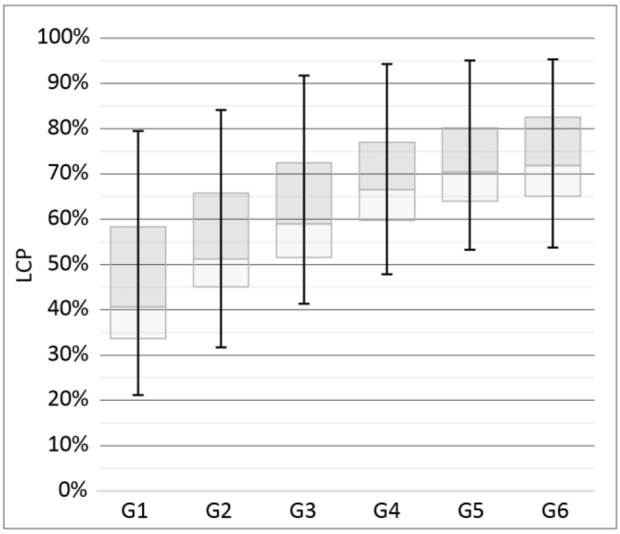

Figure 45: Boxplot showing the range of LCP for each building geometry

The boxplot indicates three main aspects: First, the ends of the vertical line (whisker) indicate the maximum and minimum LCP that can be achieved by a geometric variant. Second, the horizontal line within the box marks the median of all analysed solutions. As such, it indicates the LCP that is reached with a probability of 50%. Finally, the ends of the box indicate the first and third quartile, which means that 50% of the possible solutions possess an LCP within the range of the box. The length of the whisker and the size of the box illustrate the degree to which the geometry determines the LCP that can be achieved. Architects can use this information for deciding which geometric variant should be pursued in the following detailed design stages.

4.2.4. Discussion

The PLCP approach calculates a range of plausible solutions in each step based on assumptions for heating systems, building materials, and energy standards of the building envelope. As such, it integrates information usually only available in later design stages into the beginning of the design process, when decisions on the geometry are made. The results provide a forecast of the LCP that can potentially be achieved in later design stages. The approach allows the identification of building geometries with a high PLCP, which helps architects to choose a geometric variant for further planning stages. The results from this example show a wide range between the worst and best environmental performance of the geometric variants. As such, they indicate the great potential geometric optimization provides.

Ideally, this method frees the architect from worrying about heating systems and building materials in the early design stages, and allows them to focus on the geometry. Using this measure, architects can optimize the geometry without possessing information usually required for an LCA. Thus, it provides a solution to the dilemma that design changes to improve the environmental performance are most valuable in early design stages when information for LCA is lacking, and hard to implement in later design stages when information is available (see Section 1.3.1).

4.2.5. Summary of Section 4.2

Is the method applicable for geometry optimization and which benefits does it provide?

The optimization of building geometry was shown for a multi-family house. The aim was to apply PLCA to evaluate different geometric variants in the conceptual design stage without having information on building materials and services, in order to help the architect decide which geometry to choose for further planning. To provide a single score for the evaluation of geometric variants, a measure for the environmental performance was introduced. It is based on the DGNB certification system and referred to as life cycle performance (LCP). Six typical variants for both building materials and heating systems, and three variants for U-values were provided. The LCP was automatically calculated for all resulting possible combinations. The results indicate the great potential that geometric optimization provides, and proves that PLCA is applicable for the optimization of geometry. This approach allows architects to optimize the geometry in early design stages before the detailed information on heating systems and building materials usually required for an LCA is available.

4.3. Combined geometry and material improvement

To test the application of PLCA by non-expert LCA users during design, it was employed in a seminar that ran parallel to a student design project. As part of a joint project of the Bauhaus-Universität Weimar and the University of Mersin in the winter semester of 2014/15, nine students employed PLCA to optimize both the geometry and the materials of their designs.

4.3.1. Objective

The design task for this project consisted of developing a use scenario, choosing one of three possible sites in the historic city of Tarsus, in the south of Turkey, and finally designing the building. The project resulted in very different building types with differing intended uses, which ranged from cafés and restaurants to exhibition sites and hotels. The sustainability of their design was an important aspect of the design task and one main criteria for evaluation at the end of the semester.

Nine students from this project (Group A) who took part in the seminar were asked to analyse the life cycle environmental impact (I_{LC}) of their design every week, from the first sketches at the beginning of the semester to the final design. Any decision, from the urban setting to the size of the windows, should be made on the basis of design variants and the corresponding environmental impact. The idea was not to hinder solutions with a higher I_{LC}, but to improve understanding of the relationship between design and I_{LC}. The nine students received a short introduction to Rhinoceros, which none of them had worked with before. The functionality of CAALA was briefly explained. All geometric input and output of LCA results was realized in the viewports of Rhinoceros (see Figure 27). The students only had to input the material in GH.

The task was divided into two parts. In the first part of the semester, the students were supposed to analyse their proposed geometry and vary it in order to reduce their $I_{LC.}$ Default building materials and services were assumed to allow the students to focus on the improvement of the geometry. In the second part, the students were allowed to vary the building materials and thereby further minimize the I_{LC}.

4.3.2. Method

DBPS was used for the calculation of the heating and cooling energy demand. Computational optimizers were not employed, and the students' task was to improve the design by manual variation.

4.3.2.1. Input

Geometry

The input of the geometry was done in Rhinoceros. The individual components were drawn on predefined colour-coded layers (see Figure 27d). The geometry was automatically transferred from Rhinoceros to CAALA in GH. The level of detail corresponded to the simplified LCA. One example of the 3D model of a student’s design is provided in Figure 46.

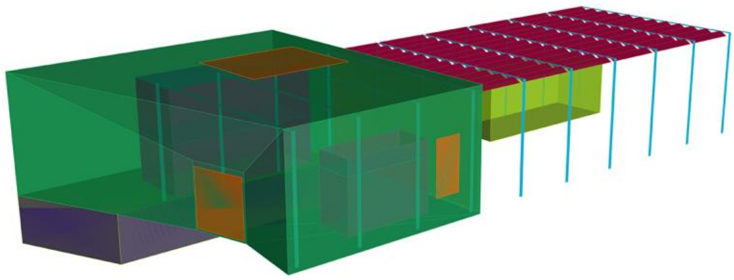

Figure 46: Input of the geometry using a colour-coded 3D model

Building materials and services

The material and thickness of each component was input in the material editor in GH. Each component was divided into four functional layers, such as exterior cladding, insulation, primary construction, and interior cladding for an exterior wall. The material could be selected from a drop-down menu; the thickness was input by means of a so-called number slider (see Figure 28).

The building services could not be selected by the students. The efficiency of the heating and cooling system was assumed to be the same in all cases. For the heating system, a gas-condensing boiler with an efficiency of 0.98 was assumed. For cooling, an electrically-powered system with an efficiency of 3.6 was assumed.

It was not possible to obtain Turkish environmental data. Therefore, all data for materials and energy carriers was taken from the combined database described in Section 3.1.1.2 based on the German ökobau.dat. Since the objective of this study was to optimize the design, this is not regarded as problematic. Although the absolute LCA results using German data might not be correct, the relative improvement through design optimization can be assumed to be accurate.

Determining factors

All determining factors were predefined and could not be changed by the students (see Table 44). The RSP was set to 50 years. In order to simplify the input and ensure comparability, internal gains were assumed to be the same for all designs, independent of the use scenario the students chose. The internal gains of a multi-family house – 90 W/m² per day according to DIN V 18599-10:2011 – were assumed. An individual setting of internal gains would have made a comparison between the designs too complex.

Climate data for Tarsus was not available. Therefore, the dataset for Izmir, provided by the US Department of Energy[90] was loaded into CAALA. It can be assumed that Izmir, which lies on the Mediterranean Sea as well, has a climate similar to that of Tarsus.

Table 44: Determining factors

RSP	50 years
Climate data	Dataset for Izmir, provided by US Department of Energy
User data	DIN V 18599-10:2011, multi-family house, page 17

4.3.2.2. Calculation

Operational impact

Cooling energy demand plays an important role in Tarsus' climate. In order to simulate the influence of shading measures in detail, DBPS was used for the calculation of the heating and cooling demand. *EnergyPlus* was used as the simulation engine, which was connected to GH with a plug-in called *Archsim.* User-related operational energy demand was not included in the LCA, because the students were intended to focus on improving building-related energy demand through the influence of their design.

Embodied impact

For the calculation of I_E, all components were considered as per the DGNB guidelines. Only the I_E of building service components was omitted, as all of the students employed the same systems and this was not part of the optimization task.

4.3.2.3. Output

In the requirement catalogue developed in Chapter 2, seven mandatory indicators are described (see Section 2.1.2). However, for students without experience in LCA, optimizing for seven criteria at the same time was regarded as too difficult. At the time of the study, the

[90] The dataset can be downloaded at: https://energyplus.net/weather-location/europe_wmo_region_6/TUR//TUR_Izmir.172180_IWEC (accessed February 9th 2016)

aggregation into a single-point indicator as described in Section 4.2.2.3 had not yet been integrated into CAALA. To simplify the output, only two indicators were used: primary energy non-renewable total (PENRT) and global warming potential (GWP). These two were chosen because they are most commonly used and have well known characterization models. A graphical output was provided which displayed the environmental impact separately for individual building components as well as the heating and cooling energy demand in the form of bar charts, in order to indicate potential for improvement. Furthermore, a pie chart was employed to indicate the share of each individual aspect within the whole building (see Figure 47).

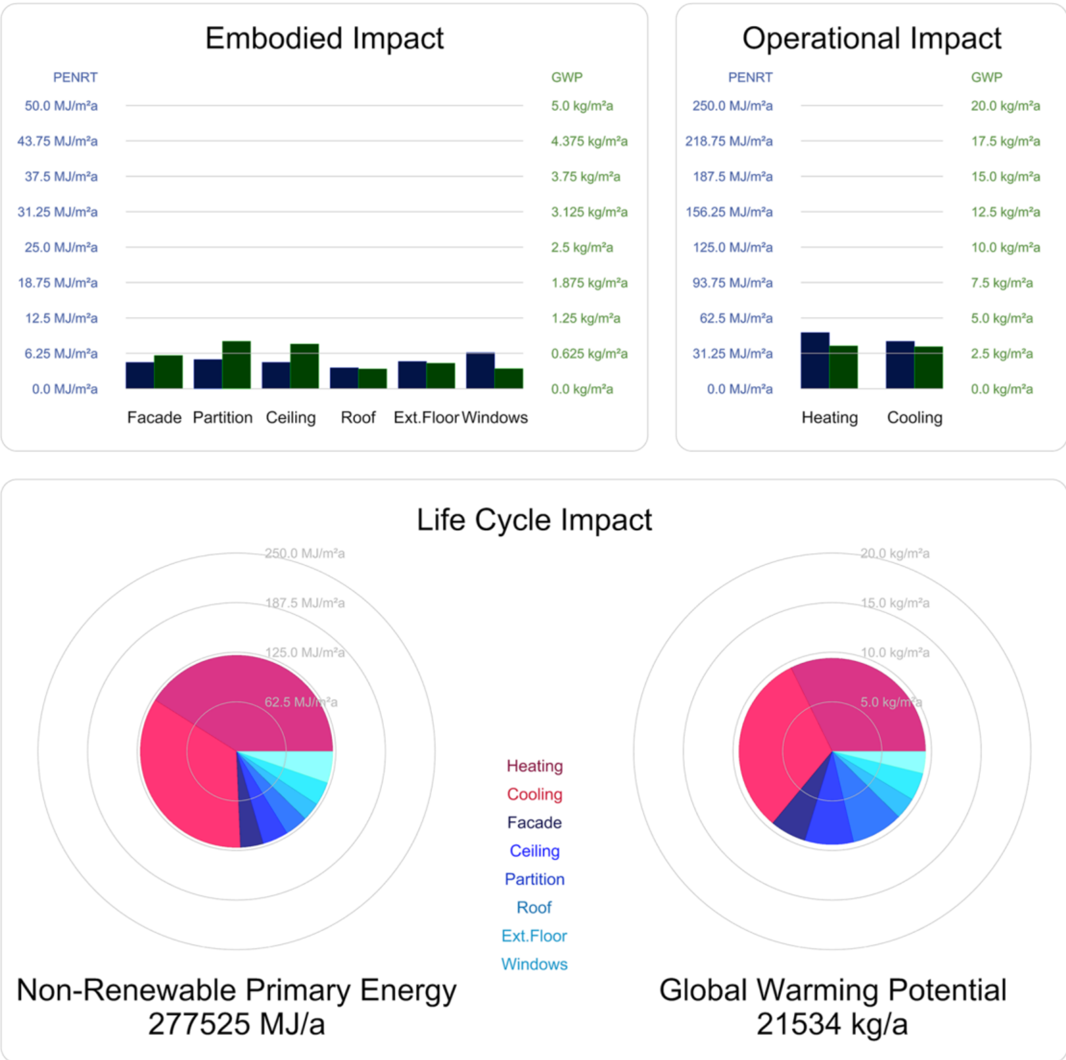

Figure 47: Visualization using bar charts and pie charts

4.3.2.4. Optimization

As noted in the description of the objective, the procedure for the semester was divided into two parts. In the first part, the students were requested to analyse their proposed geometry and vary it in order to reduce I_{LC}, measured in $PERNT_{LC}$ and GWP_{LC}. The students were requested to always consider both indicators in their decision-making. Default building materials were assumed for all components to allow the students to focus on improving the geometry (see Table 45). Data for these materials was included in CAALA in the form of default values.

Table 45: Default materials for the student design project

Component	Standard material
Exterior walls	20 cm of reinforced concrete, 6cm of EPS insulation
Interior walls	20 cm of reinforced concrete
Ceilings	20 cm of reinforced concrete
Roof	20 cm of reinforced concrete, 6cm of EPS insulation
Floor slab	20 cm of reinforced concrete, 6cm of EPS insulation

In the second part, the students were asked to vary the building materials and minimize the I_{LC}. The drop-down menu offers a range of typical building materials. To select special materials, the students were allowed to use the environmental data from EPDs and to integrate the new material into their designs. In the first part, the standard components did not include wall and floor finishing. In the second part they were included.

4.3.3. Results

The students were asked to present and explain their results every week. In the beginning, some difficulties in modelling the geometry were observed, which can be explained by their unfamiliarity with Rhino. For the simulation with EnergyPlus, all thermal zones need to be closed, and the determining factors have to be correctly assigned. As a result, the influence of changes to the geometry could not be assessed as well as desired. Data on the reduction in I_{LC} is not available for all students and therefore, the improvement of the geometry is not discussed here. However, it could be observed that most students used CAALA to improve the geometry. In particular, the window layout and shading measures were optimized to reduce cooling loads.

At the end of the semester, all of students in Group A were familiar with CAALA and able to insert custom materials. The results for default and custom materials are shown in Figure 48. The graphs show similar profiles and a visible improvement after entering the custom materials. The main differences in the values for the entire building result from the differing building sizes.

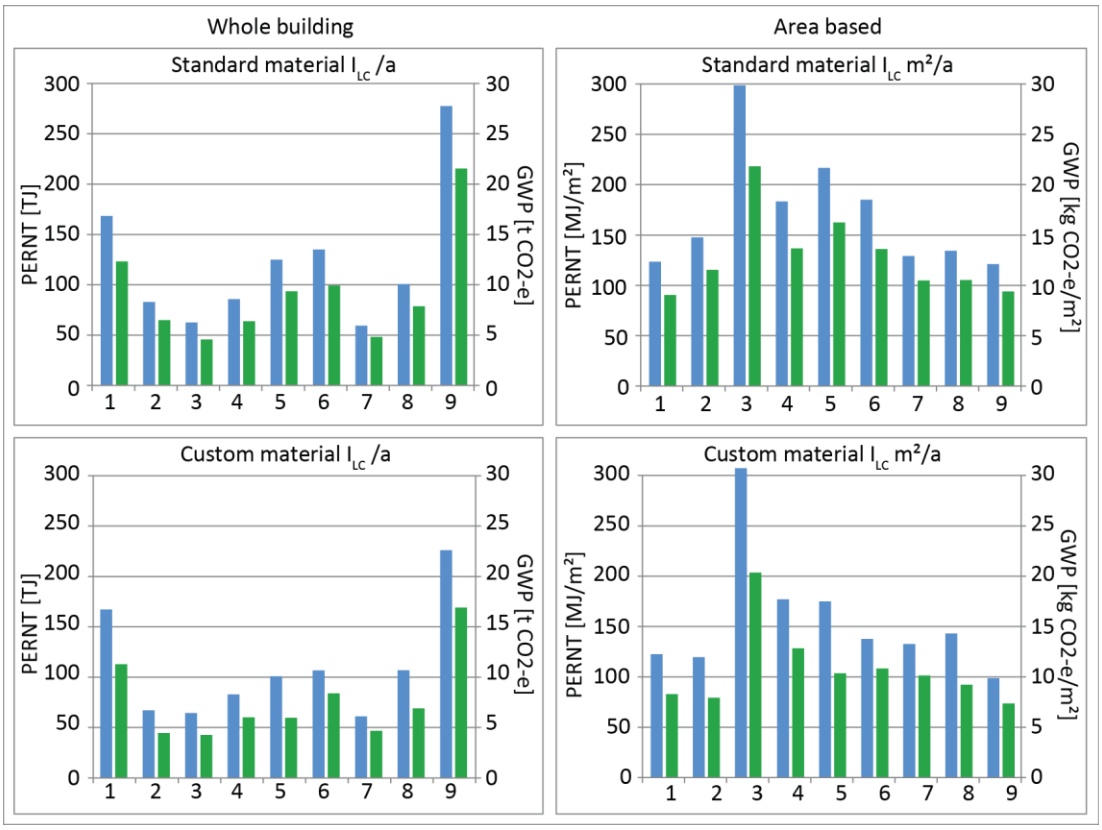

Figure 48: Results for the whole building and area based (per m^2_{NFA}) for default and custom materials (Group A)

The improvement in I_{LC} from selecting the custom materials is shown in Figure 49. On average, the students in Group A were able to reduce PENRT by 8.2% and GWP by 16.2%.

Figure 49: Improvement through custom material with both indicators (Group A)

Comparison to a reference group

Seventeen students took part in the design project without participating in the seminar, and as a result they did not apply PLCA in their projects. The designs developed by this group (Group B) were used as a comparison. At the end of the design process, the final geometry was modelled with both the default and custom building materials. Although the sustainability of the design was a main criterion in the evaluation, and the topic of embodied impact of building materials had been introduced at the beginning of the semester, the results in Figure 50 indicate that most designs perform better with the default materials. On average, application of the custom materials resulted in an increase in PENRT of 30.7% and an increase of 16.9% in GWP.

Figure 50: Improvement through custom material with both indicators (Group B)

4.3.4. Discussion

The results are discussed separately for the two parts of the semester. During the first part, the students' difficulties in modelling their designs correctly hindered the assessment of how much I_{LC} can be reduced through changes to the geometry. The problems during the first part of the semester were exclusively the result of input problems. This shows the demand for very simple graphical user interfaces and methods for inputting the geometry. One possibility could be the use of intuitive tools, such as SketchUp[91]. For the early design stages, the level of detail that these tools afford is sufficient.

The results of the second part show that all students who applied PLCA were able to reduce the I_{LC} of their design – or at least to keep it at the same level – through the choice of building materials. The greatest reduction in GWP_{LC} was achieved in Design 5. This student mainly employed wooden components. Design 7 shows no significant change in I_{LC}. The student wanted to employ exposed concrete for aesthetic reasons. Since concrete had already been the default material, it is not surprising that the results are very similar. The average reduction in $PENRT_{LC}$ of 8.2% and of 16.2% in GWP_{LC} show a significant improvement, considering that the students were neither experts in building simulation nor in LCA. The benefit of employing PLCA to analyse the environmental impact during design is shown when comparing Group A's results to those of Group B, the students who did not apply the PLCA. Only one student received better results through the choice of building materials, four stayed within the same range, but eleven students increased I_{LC}.

In general, PLCA was accepted as a support for design decisions by most of the students, although some difficulties in the beginning of the semester appeared. However, the majority of the students in Group A only compared three variants, which leads to the assumption that further improvement would have been possible if more variants had been assessed. When modelling a new variant, the students had to click a button to start the new EnergyPlus simulation. Depending on the size of the building and the performance of their computer, the simulation took between 40 seconds and 5 minutes. Although this computation time seems short enough, it proved to be a barrier to the analysis of more variants. This clearly shows the demand for feedback in real time.

4.3.5. Summary of Section 4.3

Is the method applicable for combined geometry and building material optimization and which benefits does it provide?

Nine students employed PLCA in a seminar to manually optimize both the geometric and material parameters of their building designs. In the first part of the seminar, the students were requested to analyse their proposed geometry and vary it in order to reduce the

[91] SketchUp is an intuitive 3D CAD programme by Trimble available for free at https://www.sketchup.com/download (accessed February 22nd 2016)

environmental impact. In the second part the students were asked to vary the building materials provided in a material catalogue and further reduce the environmental impact. Most students employed PLCA to improve the geometry, however the improvement based on geometric variation could not be measured. Based on the material optimization, all students were able to reduce the impact of their design, for average reductions in $PENRT_{LC}$ of 8.2% and 16.2% in GWP_{LC}. In general, PLCA was accepted as a support for design decisions, which shows that it is applicable by non-expert users. The majority of the students only compared three variants, which leads to the assumption that further improvement would have been possible if more variants had been assessed. Nevertheless, this example shows that PLCA can significantly improve a building design, even when using a small number of variants.

4.4. Requirement evaluation

As noted in the introduction to Chapter 4, the main aim of this chapter is to evaluate the developed method. The previous three sections describe the application of PLCA in different scenarios. PLCA is evaluated in this section based on these examples of application. The evaluation consists of two parts. The first part analyses whether PLCA fulfils the criteria of the requirement catalogue established in Chapter 2. The questions from the requirement catalogue are answered and the necessary documentation is provided. The second part discusses the time-efficiency of PLCA by comparing the reduction in environmental impact to the time needed for application in each of the three examples. The average time needed for PLCA is also compared to the average time of commercial approaches for the LCA of buildings.

4.4.1. Requirements

In this first part of the evaluation, the requirement catalogue developed in Section 2.5 (see Table 25) is applied to check whether the method fulfils the requirements. The documentation for each requirement is provided for each workflow step in the following. The completed checklist is provided at the end of the section (see Table 47).

4.4.1.1. Input

Life cycle modules (M): In all examples (excluding the supplementary example in section 4.1.5), the combined database described in Section 3.1.1.2 was employed. This database includes the life cycle modules A1-A3, C3, C4, and D. In the supplementary example in Section 4.1.5, the KBOB database was employed, which also includes these life cycle modules. Module B4 is integrated by calculating the number of necessary replacements (see Section 3.1.2.2). Module B6 is calculated by using energy demand calculation and multiplying the result by the specific operational impact factor (see Section 3.1.2.1). Therefore, all mandatory life cycle modules are included, and this requirement is fulfilled for all of the case studies.

Environmental indicators (M): All mandatory indicators for simplified LCA have been integrated into the combined database. As such, they are included in all examples that use this database. In the example from Section 3.3, the students only used PENRT and GWP as criteria for their design optimization. The simplification was made to prevent overloading the students. Nevertheless, all indicators were calculated in the background. Thus, the exclusion of indicators results from the teaching approach, not due to a failure of the method. The supplementary example in Section 4.1.5 which uses KBOB databases only includes PENRT, GWP, and eco points (UBP). Because the main focus of this example was showing the extended functionality of PLCA when including cost analysis, the requirements are regarded as fulfilled in all cases.

Environmental data quality (M): The examples from Sections 4.1 and 4.2 are located in Germany. As such, the use of ökobau.dat is suitable for the geographic context. No Turkish data could be found for the projects located in Tarsus (see Section 4.3). Therefore, ökobau.dat was employed.

Ökobau.dat version 2011 was employed for all examples, because this is the only version integrated into eLCA, where the datasets for production are linked with the respective EOL and RSL data. At the time the case studies were carried out (2012 to 2015), some datasets had lost their time validity. As such, this requirement can only be regarded as partially fulfilled. As soon as the ökobau.dat version 2015 is integrated into eLCA, this data can be employed and the requirement can be regarded as fulfilled. It can be assumed that data availability will improve in Europe in the coming years, as there are different projects for harmonization ongoing[92]. This should result in fewer difficulties finding valid datasets.

Minimum building components to be included in the 3D model (M): As described in Section 3.1.1.1, the geometry can either be input using CAD software or directly using parametric design software. In both cases, the geometry is input using a 3D model. As such, the requirement for a 3D model for the geometry input is always fulfilled.

In the refurbishment scenario in Example 1, load-bearing structures which are not part of the thermal envelope, e.g. ceilings or load-bearing interior walls, were not included. It was assumed that these building components provided their function for the RSP of 30 years without any replacement. As such, their I_E was set to zero. With this assumption, the requirement of including the primary load-bearing structure in the input is fulfilled. In the new construction in Example 2 and 3, all minimum components, including exterior walls, windows, roofs, ceilings, slabs, foundations, interior walls, columns, and building services have been considered. As such, this requirement is fulfilled. For screenshots of the 3D models, see Figure 38, Figure 42, and Figure 46.

[92] The extension of ökobau.dat with datasets of other European countries was discussed at Sustainable Built Environment 2016 in Hamburg, see http://www.bbsr.bund.de/BBSR/DE/Aktuell/Veranstaltungen/Programme-2016/DL/2016-03-08-hh-lca.pdf?__blob=publicationFile&v=6 (accessed March 30th, 2016)

Reference Service Period (M/O): The RSP is declared in every example. As such, the mandatory requirement is fulfilled. The default RSP of 50 years was used in Examples 2 and 3. In the case of refurbishment in Example 1, the RSP was adjusted to 30 years, which was assumed to be more realistic for this existing building. This shows that PLCA allows for easy adjustment of the RSP. Because the RSP is parametrized in the LCA model (see Figure 22), it can quickly be adjusted to any number and enables comparison of different scenarios. Therefore, the optional requirement is also fulfilled.

Predefined values (O): Predefined values for building materials and services are integrated in the building catalogue described in Section 3.1.1.2. The application of these values is shown in Example 2. The assumptions for the predefined building components employed are described in Appendix F. As those represent typical components for construction in Germany, this requirement is fulfilled.

4.4.1.2. Calculation

Combined calculation of I_E and I_O (M): As shown in Figure 22, the calculation of I_O and I_E are interlinked in the parametric LCA model, which is the core of the method developed for this thesis. In all examples I_O and I_E were calculated simultaneously. Because this requirement is incorporated into the basic structure of the parametric model, it is always fulfilled.

Operational energy demand (M): In all of the examples, the energy demand for space heating is calculated individually for the specific situation of the building using either QSSM with monthly time steps or DBPS with hourly time steps. In Examples 1 and 2, it was assumed that no active cooling is needed. In Example 3, the cooling demand was also calculated using DBPS with hourly time steps. Therefore, this requirement has been fulfilled in all case studies.

4.4.1.3. Output

Visualization of results (O): Examples of the potential for visualization that PLCA provides are shown in Figure 44 and Figure 47. Therefore, this requirement is fulfilled.

Single-score indicator (O): A single indicator based on the DGNB certification system was employed to evaluate different design variants in Example 2. This shows that PLCA allows for integration of normalization and weighting methods. The weighting procedure is described in detail in Appendix B. Therefore, this requirement can be regarded as fulfilled. Furthermore, PLCA allows for parametrically changing the weighting, which has not been employed in the case studies.

Information on data uncertainty (O): As explained in Section 2.3.3, databases of building material environmental data do not include information on the uncertainty in the data. Therefore, this information could not be included in the combined database developed for this thesis and could not be output in the examples shown here. Once this information is available in the future, it can easily be integrated. Until then, however, this requirement is not fulfilled.

4.4.1.4. Optimization

Self-contained workflow (M): As shown in Figure 22, the main characteristic of the parametric model is the self-contained workflow loop to allow for optimization. Furthermore, all input is parametrized (see Section 3.1.1), enabling computational optimizers to be employed. Therefore, this requirement is always fulfilled.

Maximum time for application (M): The total time needed for the application of PLCA including optimization in each example is provided in Table 46. It can be seen that the total time is less than 8 hours in each case. Therefore, this requirement is fulfilled in all examples.

Table 46: Overview of time needed for application

	Example 1 (Scenario A)	Example 2	Example 3 (average of Group A)
Total time needed for application	5 hours	5 hours	6 hours

4.4.1.5. Checklist requirements

The results of the evaluation using the checklist are indicated in Table 47.

Table 47: Checklist of requirements for environmental building design optimization methods based on LCA

Step	Requirement	*	Question	Y	N	Documentation
Input	Life cycle modules	M	a) Screening LCA: Are at least the life cycle modules A1-A3, and B6 included? b) Simplified LCA: Are A1-A3, B4, B6, C3, C4, and D included?	✓		Declaration of life cycle modules included
	Environmental indicators	O	a) Screening LCA: Are at least three indicators covering different environmental problem fields included? b) Simplified LCA: Are PET, PENRT, GWP, EP, AP, ODP, and POCP included?	✓		Declaration of environmental datasets employed and output of the respective indicators
	Environmental data quality	M	Is the environmental data valid?	0		Declaration of environmental datasets employed
	Minimum building components to be included in the 3D model	M	a) Screening LCA: Are the building envelope and the primary load-bearing structure included? b) Simplified LCA: Are exterior walls, windows, roofs, ceilings, slabs, foundations, interior walls, columns, and building services included?	✓		Screenshot of the 3D model and description the components included
	Reference Study Period	M	Is the assumed RSP declared?	✓		Declaration of the RSP
		O	Can the RSP be adjusted?	✓		Description of the adjustment
	Predefined values	O	Are predefined data based on the most typical building components provided?	✓		Declaration of predefined values
Calculation	Combined calculation of I_E and I_O	M	Are the modules of I_E (A1-A3, B4, C3, C4 and D) and of I_O (module B6) linked and calculated together?	✓		Description of the calculation algorithms
	Operational energy demand	M	Is the energy demand for space heating and cooling calculated using at least monthly time steps?	✓		Description of the method used for energy calculation including the time steps
Output	Visualization of results	O	Is a graphic output provided?	✓		Screenshot of graphic output
	Single-score indicator	O	Is a single-score indicator output in addition to the midpoint indicators?	✓		Output of a single indicator and description of the weighting method
	Information on data uncertainty	O	Is information on data uncertainty included in the output?		X	Output of information on uncertainty of environmental and RSL data
Optimization	Self-contained workflow	M	Is the method's workflow self-contained?	✓		Description of the calculation algorithms and the workflow
	Maximum time for application	M	Is the time needed for application less than 8 hours for residential buildings / 16 hours for complex buildings?	✓		Declaration of the time needed to apply the method

* Mandatory (M) or optional (O) requirement

✓ requirement fulfilled X requirement not fulfilled 0 requirement partly fulfilled

4.4.2. Time-efficiency

As described in Section 2.4.2, the reduction in impact and the time necessary for application of the method have to be measured to evaluate the time-efficiency. This is done separately for each example.

4.4.2.1. Impact reduction

As noted in Section 2.4.2, the optimized solution can be compared to a benchmark or a baseline solution to measure the reduction in impact. The baseline solution was chosen specifically for each example.

Example 1

To evaluate the reduction in environmental impact, a baseline scenario for a typical refurbishment measure was provided which includes a gas-condensing boiler with an efficiency of 98%, 20 cm of EPS insulation, and exchange of the original single pane windows for double glazing. The results for these baseline solutions are shown in Table 48. Table 48 also indicates the optimum for each indicator based on Figure 39 and the improvement in comparison to the baseline scenario. For each optimum, a different combination of heating system, insulation material, insulation thickness, and window type is required. As such, the improvement shown in Table 48 only represents the potential improvement for each indicator. The optimum cannot be achieved at the same time for all indicators. As described in Section 4.1.4, a single indicator as employed in Example 2 would be useful to help the architect make a decision. Nevertheless, the comparison indicates the great improvement potential that PLCA can identify.

Table 48: Difference between baseline scenario and optimum

	Baseline scenario	Optimum solution	Difference	Improvement
PET [MJ]	1043594	360760	682833	65.4%
PENRT [MJ]	1041500	18506	1022994	98.2%
GWP [kg CO_2-e]	61314	-54384	115698	188.7%
ODP [kg R11-e]	1.15E-04	3.59E-06	1.11E-04	96.9%
AP [kg SO_2-e]	54.93	1.59E-04	54.93	100.0%
EP [kg PO_4^{3}-e]	1.15	4.40E-11	1.15	100.0%
POCP [kg C_2H_4-e]	22.77	0.53	22.23	97.7%
ADPE [kg Sb-e]	1.83E-02	-3.40E-02	5.23E-02	285.8%

Example 2

The aim of this example was to indicate the potential life cycle performance that different geometric variants possess. To evaluate the life cycle performance (LCP), a single indicator based on DGNB was established. Since no classic optimization process was carried out, it is difficult to exactly quantify the reduction in environmental impact. As Table 49 indicates, the median of the geometry with the worst environmental performance was 41% of the LCP that could possibly be achieved according to the DGNB certification system. The median of the best geometry was 72% of LCP (see Section 4.2.3). This equates to an improvement of 31 percentage points according to the DGNB certification, solely based on the geometry (see Table 49), which indicates the great potential geometric optimization provides.

Table 49: Improvement based on geometry variation

	Worst geometry	Best geometry	Improvement
LCP (median)	41%	72%	31 percentage points

Example 3

The results provided in Section 4.3.3 indicate that all students who applied the tool were able to reduce the environmental impact of their design through the choice of building materials. The average reduction in $PENRT_{LC}$ of 8.2% and 16.2% in GWP_{LC} based on their choice of material shows a significant improvement, especially considering that the students were neither experts in building simulation nor in LCA. In comparison to Group B, who did not apply PLCA, the buildings designed by the students from Group A achieve an average of 42.7% less $PENRT_{LC}$ and 41.1% less GWP_{LC} (see Table 50).

Table 50: Comparison of results between Group A and B

	Group A	Group B	Difference	Improvement
$PENRT_{LC}$ [MJ/m² a]	156.99	273.98	116.99	42.70%
GWP_{LC} [kg CO_2-e/m² a]	10.82	18.36	7.55	41.11%

As noted in Section 4.3.4, the majority of the students in Group A only compared three variants, which leads to the assumption that further improvement would have been possible if more variants had been assessed.

4.4.2.2. Time needed for application

The time needed for application of PLCA is divided into time for input of the first variant and time for further variants in the optimization process, and is described separately for each example. At the end of this section, the results are summarized (see Table 51) and compared to conventional LCA approaches for buildings.

Example 1

Geometry input for the single-family house took approximately 30 minutes in Rhinoceros. The original material had to be added to the combined database in order to be loaded into CAALA, which took about two hours. The choice of insulation materials and heating systems took about two more hours. Running the loop of all 11529 possible solutions in Scenario A took about 20 minutes, which equates to 0.1 seconds per variant.

In Scenario B, the evolutionary algorithm was used to find the optimum within an extended search space of more than 300 million possible solutions. Within 15 minutes, the optimum (or a solution very close to the optimum) was found. As discussed in Section 2.4.2, the time required for optimization depends not only on the method used to calculate the LCA, but also on the optimization algorithms employed. Using a more efficient optimizer might lead to the optimum solution faster.

Example 2

The six geometric variants were drawn in Rhinoceros, which took less than two hours. The selection of building materials and building services took about three hours. All variants were input at the same time, but it can be assumed that the first variant would have taken about three hours and further variants about two hours. For each geometry, 108 variants of building materials and services were calculated by running a loop, which took 70 seconds each.

Example 3

All students were first-time users of Rhinoceros. The size and complexity of their geometric models varied a great deal. On average, the students needed about five hours to draw the geometry. They modified the geometry throughout the design process, but as described in Section 4.3.3, data on reductions in environmental impact through geometric variation is not available for all students and not discussed here. All students required less than 1 hour to calculate three building material variants. For each new variant, the students had to start an EnergyPlus simulation, which took between 40 seconds and 5 minutes. This proved to be a barrier to the analysis of more variants (see Section 4.3.3).

Overview and comparison

Table 51 provides a summary and an overview of the time needed for application in each example. The time per variant is also indicated.

Table 51: Time needed for application in detail

	Mean value of tested commercial tools (see Table 20)	Example 1 (Scenario A)	Example 2	Example 3 (average of Group A)
Number of variants	1	11529	648	3
Total time	4 days	5 hours	5 hours	6 hours
Time for 1st variant	3.5 days	4.5 hours	3 hours	5 hours
Time for further variants	5.5 hours	20 minutes	2 hours	1 hour
Time per variant	5.5 hours	0.1 seconds	< 6 minutes	approx. 20 minutes

To compare the time needed for the application of the PLCA with the time needed using conventional, commercial tools, the time for Example 3 is compared to the average of the tools described in Section 1.4.2.1 (see Table 20). It can be assumed that the students using PLCA in Example 3 had the same level of knowledge as the students using the commercial tools. All of them were first-time users of the specific software and had never carried out an LCA before. Table 51 indicates that, in comparison with the conventional commercial tools, PLCA is much more time-efficient. The input of the first variant took 5 hours on average. Compared to the 3.5 days (which equals about 28 hours) needed on average for the input using commercial tools, this means it is more than five times faster. On average the students needed 5.5 hours to calculate one variant using commercial tools. The students using PLCA only needed about 20 minutes, which makes PLCA more than 16 times faster in manual variant generation and evaluation. Furthermore, it should be considered that the students in Example 3 always calculated both operational and embodied environmental impact, while the students using conventional tools only calculated the embodied impact.

4.4.2.3. Checklist time-efficiency

The results for time-efficiency in each example are summarized in Table 52.

Table 52: Checklist for measuring time-efficiency

	Example 1	Example 2	Example 3
Reduction in environmental impact	More than 65%	31%	More than 40 %
Time needed for the first design variant	4.5 hours	3 hours	5 hours
Time needed for design optimization	20 minutes	2 hours	1 hour

4.4.3. Summary of Section 4.4

Which requirements established for the development of the method are fulfilled?

PLCA fulfils all mandatory requirements. Only one requirement concerning the time-validity of the environmental data employed is only partially fulfilled in some examples of application. This is due to the lack of combined data, which will soon be remedied. New data can easily be used for PLCA and ensure that this requirement is fulfilled in the future. PLCA also fulfils all optional requirements, except the information on uncertainty. This is also due to a lack of information in the environmental and RSL databases. Once this information is readily available, it can be employed in PLCA, and this requirement will be fulfilled.

How much of a reduction in environmental impact is possible, and how much time is needed for the application of the method?

The environmental impact of the design could be significantly reduced in all three examples. The improvement ranged from 31% in Example 2, to 40 % in Example 3, to more than 65% in Example 1.

The time needed for application of PLCA was divided into time for the first variant and time for further variants in the optimization process. The time required for the first variant ranged between 3 and 5 hours, compared to about 2-3 days using conventional approaches. The time needed for the LCA of further variants ranged between 0.1 second per variant in the case of computational optimization and 20 minutes per variant when using manual improvement. The comparison to currently available commercial tools shows that PLCA is more than five times faster for the calculation of the first variant, and more than 16 times faster for further variants in the optimization process.

4.5. Summary of Chapter 4

Can the parametric method be employed for environmental optimization in architectural design, and which requirements are fulfilled?

The parametric method was applied in three different examples, each with a different focus. The first example showed that PLCA is applicable for building material optimization using computational optimizers. Within a short time period of 15 minutes, the optimum within a search space of more than 300 million possible solutions was found. The second example presented the potential that PLCA offers for geometric optimization using a semi-automatic approach in early design stages. Based on a set of assumptions, LCA could be calculated before information about building materials and services was available. In the third example, nine students employed PLCA for combined manual optimization of material and geometry. The comparison of results to a reference group indicates that a reduction in environmental impact of more than 40% was possible using PLCA. In Example 1 and 2 the reductions were 65% and 31% respectively.

These examples also served to evaluate PLCA based on the requirement catalogue. All mandatory and all but one optional requirements have been fulfilled. The analysis of the time-efficiency of the method indicates that PLCA is more than five times faster than current available approaches in calculating the LCA of a first design variant. When calculating further variants for design optimization, PLCA is more than 16 times faster, while providing the same quality of results, as proved by fulfilling the mandatory requirements.

Conclusion and outlook

This final chapter provides a conclusion and an outlook on future possibilities for research based on this thesis.

a) Conclusion

The method developed in this thesis – *Parametric Life Cycle Assessment* (PLCA) – minimizes the effort of performing an LCA for buildings by incorporating a simplified LCA into the design process. As such, PLCA allows architects to focus on the main task of designing the building. By providing architects with this novel method, the current discontinuous and inefficient workflow of LCA for buildings in the design process (see Figure 2 in introductory Section b), which can lead to sub-optimal solutions, is avoided. The steps necessary for conducting LCA for buildings are combined into one method, providing a continuous workflow (see Figure 51). As a result, LCA results can be provided to architects within less than a second, instead of the hours necessary using conventional approaches. Furthermore, this unique workflow allows for optimization. The input variables – geometry, building materials and services – can be easily modified to generate, calculate, and compare many variants. The optimization process can be either carried out manually by the architect or computational optimizers can be employed. Most importantly, the interrelation between the operational and embodied impact is always maintained, in order to guarantee holistic solutions. As such, the method is the first of its kind that allows for time-efficient, holistic optimization of both operational and embodied impacts.

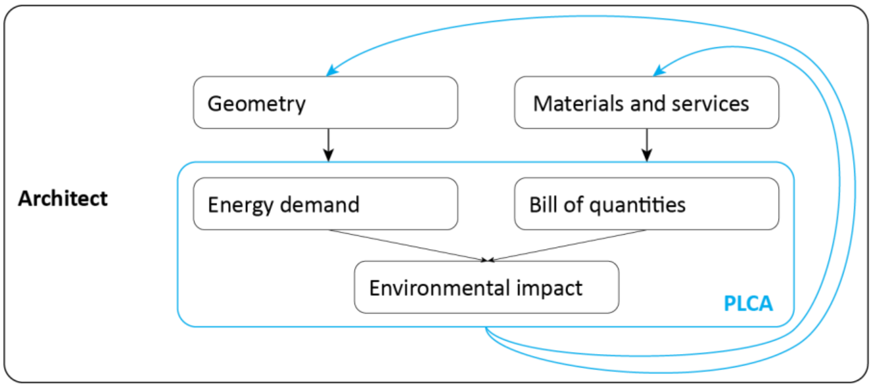

Figure 51: Process of LCA in architectural design using PLCA

The current dilemma inherent to LCA in architectural design is that once the necessary information is available – usually in design stage 4 – the LCA results are difficult to implement. Using the parametric approach and adequate assumptions for missing information enables the application of LCA to be shifted from design stage 4 to stage 2, and therefore provides a solution to this dilemma. Now, building designs can be time-efficiently optimized from the beginning of the most influential early design stages.

The examples provided in Chapter 4 demonstrate PLCA to be applicable for the optimization of both geometry and building materials. The evaluation of the LCA results show the large reduction in environmental impact that can be achieved in all three examples. Independent of the optimization approach – manual or computational – and the design task – new construction or refurbishment – a reduction in environmental impact of at least 30% could be achieved. Furthermore, the application examples clearly indicate the time-efficiency of PLCA. In Example 1 (see Section 4.1), the optimum within a search space of more than 300 million possible solutions could be found within 15 minutes, for example. Comparing the time students needed for application in Example 3 (see Section 4.3) showed that PLCA is also much faster than conventional approaches to manual variant comparison. While being much faster, PLCA provides at least the same quality of LCA results as conventional approaches, which has been demonstrated by fulfilling the mandatory requirements established in the requirement catalogue. The large reduction in the environmental impact achieved by the students showed that optimization is possible for non-experts. Nevertheless, the expertise of energy consultants and LCA practitioners is necessary for intricate problems, detailed building simulation, or a complete LCA in later design stages. PLCA does not replace these experts. Rather, it provides the possibility for architects to time-efficiently use LCA for design optimization as one criterion within other design criteria. Until now, this has not been possible within a realistic timeframe and was too labour-intensive to be practical.

PLCA does not only provide benefits for architects. By using the parametric model, experts usually involved in later design stages, such as energy consultants and LCA practitioners, already have a basis for their work and can save much time usually needed to gather information. Energy consultants can use the model to carry out the mandatory calculations for energy performance certificates and their effort for the input is very significantly reduced. LCA practitioners can use the model to carry out the LCA for building certification and for documentation purposes. Besides these benefits in practice, PLCA can be used for scientific purposes. The time-efficient method allows for extensive studies including many more buildings than are possible in current research studies to determine advanced national benchmarks for LCA, for example. Finally, PLCA can influence national and European legislation for building regulations. Figure 1 in the introduction of this thesis clearly shows the demand for assessing the whole life cycle of buildings. The integration of LCA in building regulations is necessary to achieve the European climate targets in the building sector. PLCA reduces the effort of an LCA to the effort of the currently mandatory energy performance certificates. As such, it demonstrates that a mandatory LCA for buildings is practically feasible, reasonable, and could be integrated into regulations.

b) Outlook

The flexibility of PLCA allows for many further developments in the future. Life cycle modules neglected in this thesis could easily be integrated in the future, if the environmental data becomes available. Once more environmental datasets for further building services, such as thermal storages, batteries, and building automation are available, they should be integrated, because this will provide further potential for environmental optimization. In addition, currently available common environmental indicators do not cover all environmental problem fields. Once more indicators are available they can be integrated into the combined database and used with PLCA.

The use of predefined values for building materials allows for the application of PLCA in early design stages when detailed information is not completely available. As noted in Section 2.1.6, these assumptions would ideally be based on the most common building materials and services for a specific building type and region. In order to define which material or building service is most common, a great number of reference buildings must be analysed. Such an elaborate study has not yet been carried out. Databases used for cost estimation such as BKI[93], could serve as a data source, for example. This analysis would be labour-intensive, but further simplify the application of LCA in architectural design to a great extent.

As mentioned in Section 1.2.1.5, uncertainty is a big challenge for the application of LCA, and was not included in PLCA, as information about uncertainty in the data is not integrated in environmental databases yet (see Section 2.3.3). In addition to uncertainty in environmental and RSL data, the operational energy demand resulting from the influence of the user is very uncertain. In the future, PLCA could provide the potential for integrating theses aspects of uncertainty. Due to its potential for quickly calculating variants, different scenarios including best and worst cases for the different sources of uncertainty could be calculated. For more advanced research, the distribution of the uncertain parameters could be included using methods such as Monte Carlo simulation. Instead of single numeric values, the LCA results could then be output in ranges, indicating the probability of achieving a certain result. To visualize this information, scatter plots or box plots could be used, for example. This would be similar to the graphic output from Example 2 in this thesis (see Figure 45). In addition to uncertainty, the influence of individual input parameters on the overall LCA results could be

[93] BKI stands for *Baukosteninformationszentrum Deutscher Architektenkammern* (Cost Information Centre of the German Chamber of Architects). They publish data on reference buildings after construction. See http://www.baukosten.de/ (accessed May 4th 2016)

investigated using sensitivity analysis. Furthermore, by combining the information on uncertainty and sensitivity, robust solutions could be identified. These represent designs that might not achieve the optimum using mean values, but perform well in all cases, including best and worst case scenarios. This information would be very valuable for decision-makers, and would help to overcome the current reservations towards employing LCA in practice due to the high uncertainties involved.

Here, the method was employed for individual buildings with a focus on residential buildings. All other types of buildings could be similarly optimized using PLCA. The main difference would be the calculation of the operational energy demand, but the general approach of the method is identical. In the future, PLCA could also be employed for the assessment of neighbourhoods consisting of different types of buildings. Currently, the research focus in the literature lies on using synergy effects within an urban quarter relating to energy efficiency in the use phase. LCA should be employed to guarantee a holistic benefit throughout the lifecycle of a quarter. In particular, because of the simplicity of the 3D model, PLCA would provide an efficient means of assessment for quarters.

Further performance-analysis capabilities could be integrated in the future. For example, static analysis could be integrated to optimize load-bearing structures. As they make up a great part of embodied impact, they constitute a large potential for optimization.

Another topic is the integration of life cycle costing (LCC) into PLCA. The LCC method shows some different characteristics, but the general concept is very similar to LCA. The assessment of the costs throughout the whole life cycle in the design stages is of high interest to decision-makers who do not sell the building after construction but use it themselves, such as owners of single-family houses, building cooperatives, or public buildings owned and operated by a city. In these cases, the combination of LCC and LCA provides the potential to convince decision-makers to choose a more environmentally friendly solution with higher investment costs if it is economically worthwhile in the long term. Once a common ground for the evaluation of the social aspects has been developed, PLCA can also be extended for social life cycle assessment (SLCA). Then, PLCA would be able to assess all three pillars of sustainability and be applicable for life cycle sustainability assessment (LCSA).

As shown here, PLCA provides a good starting point for further research. As the world's population is growing and resources are becoming scarcer, sustainability will become even more important in the future. Architects and planners have great potential to enhance sustainability in the building sector. Applying PLCA in the design process today is one step towards more environmentally friendly buildings.

References

Ahbe, S. et al., 2014. *Methode der ökologischen Knappheit für Deutschland – Eine Initiative der Volkswagen AG*, Berlin: Logos Verlag.

Ahuja, S. et al., 2015. Practical energy and cost optimization methods for selecting massing, materials, and technologies. In *Architectural Research Centers Consortium ARCC*. Perkins + Will.

AIA, 2012. *An Architect's guide to integrating energy modeling in the design process*, Available at: http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab096060.pdf.

AIA, 2007. *Integrated Project Delivery: A Guide*, Available at: http://www.aia.org/groups/aia/documents/pdf/aiab083423.pdf.

AIA CC, 2014. *Integrated Project Delivery: An Updated Working Definition*, Available at: http://www.aiacc.org/wp-content/uploads/2014/07/AIACC_IPD.pdf.

Antón, L.Á. & Díaz, J., 2014. Integration of LCA and BIM for Sustainable Construction. *International Journal of Social, Management, Economics and Business Engineering*, 8(5), pp.1345–1349.

Attia, S. et al., 2009. Architect Friendly: a Comparison of Ten Different Building Performance Simulation Tools. *Eleventh International IBPSA Conference*, 1(1), pp.204–211.

Attia, S. et al., 2013. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy and Buildings*, 60, pp.110–124.

Aurélio, M., Benetto, E. & Koster, D., 2011. Environmental life cycle assessment and optimization of buildings. In *LCM 2011*.

Ayres, R.U., 1995. Life cycle analysis: A critique. *Resources, Conservation and Recycling*, 14(3-4), pp.199–223.

Bahadir, M., Parlar, H. & Spiteller, M., 2000. *Springer Umweltlexikon* M. Bahadir, H. Parlar, & M. Spiteller, eds., Berlin, Heidelberg: Springer Berlin Heidelberg.

Bahr, C. & Lennerts, K., 2010. *Lebens- und Nutzungsdauer von Bauteilen*, Forschungsprogramm „Zukunft Bau".

Baitz, M. et al., 2012. LCA's theory and practice: like ebony and ivory living in perfect harmony? *The International Journal of Life Cycle Assessment*, 18(1), pp.5–13.

Barrett, J. et al., 2002. Technical Report: A Material Flow Analysis and Ecological Footprint of York. , (October 2015), pp.5–129.

Basbagill, J. et al., 2013. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, 60, pp.81–92.

Bates, R. et al., 2013. Quantifying the Embodied Environmental Impact of Building Materials During Design: A Building Information Modeling Based Methodology. In *PLEA*. Munich, pp. 1–6.

BbgBO, 2008. *Brandenburgische Bauordnung*, Available at: https://bravors.brandenburg.de/br2/sixcms/media.php/76/GVBl_I_14_2008.pdf.

BBSR, 2011. Wohnhäuser mit Plus-Energie-Niveau - Definition und Berechnungsmethode. , p.2. Available at: http://www.nachhaltigesbauen.de/aktuelles/aktuelle-informationen/aktuelle-informationen-detail/article/2011/08/19/foerderprogramm-fuer-energie-plus-haeuser-aufgelegt.html.

Berardi, U., 2012. Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings. *Sustainable Development*, 20(6), pp.411–424.

Berger, M. & Finkbeiner, M., 2010. Water Footprinting: How to Address Water Use in Life Cycle Assessment? *Sustainability*, 2(4), pp.919–944.

Bigalke, U. et al., 2012. *Der dena-Gebäudereport 2012. Statistiken und Analysen zur Energieeffizienz im Gebäudebestand.*,

Björklund, A.E., 2002. Survey of approaches to improve reliability in lca. *The International Journal of Life Cycle Assessment*, 7(2), pp.64–72.

Blasco, X. et al., 2008. A new graphical visualization of n-dimensional Pareto front for decision-making in multiobjective optimization. *Information Sciences*, 178(20), pp.3908–3924.

BMWi, 2010. *Energiekonzept für eine umwelt schonende, zuverlässige und bezahlbare Energieversorgung*,

Bonnet, R. et al., 2014. Simplified and reproducible building Life Cycle Assessment: Validation tests on a case study compared to a detailed LCA with different user' s profiles. In *World Sustainable Building*. pp. 276–283.

Borucke, M. et al., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. *Ecological Indicators*, 24, pp.518–533.

Boustead, I., 1996. LCA — how it came about. *The International Journal of Life Cycle Assessment*, 1(3), pp.147–150.

Braune, A., 2014. *Ökobilanz-Benchmarks für Immobilien Methode zur Entwicklung zukunftsorientierter Kennwerte für eine lebenszyklusbasierte Bewertung der ökologischen Nachhaltigkeit von Immobilien*, Fraunhofer Verlag.

Brundtland Commission, 1987. *Our Common Future*, Available at: http://conspect.nl/pdf/Our_Common_Future-Brundtland_Report_1987.pdf.

Brunner, P.H. & Rechberger, H., 2004. *Practical Handbook of Material Flow Analysis*, Lewis Publishers

Bucci, F. & Mulazzani, M., 2002. *Luigi Moretti: Works and Writings* Translated., Princeton Architectural Press.

Bundesregierung, 2013. *EnEV 2014: Energieeinsparverordnung - Nichtamtliche Lesefassung zur Zweiten Verordnung zur Änderung der Energieeinsparverordnung vom 18. November 2013*, Germany: Bundesanzeigerverlag.

Carlos, J.S. & Nepomuceno, M.C.S., 2012. A simple methodology to predict heating load at an early design stage of dwellings. *Energy and Buildings*, 55, pp.198–207.

Carlowitz, H.C. von, 1713. *Sylvicultura Oeconomica - Oder Haußwirthliche Nachricht und Naturmäßige Anweisung Zur Wilden Baum-Zucht*, Leipzig.

Cato, M.S., 2009. *Green Economics: An Introduction to Theory, Policy and Practice*, London: Earthscan.

Ciroth, A. et al., 2013. Empirically based uncertainty factors for the pedigree matrix in ecoinvent. *The International Journal of Life Cycle Assessment*, pp.1–11.

Ciroth, A., 2006. *Fehlerrechnung, Datenqualität, Unsicherheit*,

Citherlet, S., 2001. *Towards the Holistic Assessment of Building Performance Based on an Integrated Simulation Approach*. Swiss Federal Institute of Technology (EPFL).

Coello, C.A.C. & Christiansen, A.D., 1999. Moses : a Multiobjective Optimization Tool for Engineering Design Optimization Tool. *Engineering Optimization*, 31(3), pp.337–368.

Coello, C.C., Lamont, G.B. & Veldhuizen, D.A. van, 2007. *Evolutionary Algorithms for Solving Multi-Objective Problems* 2nd ed., Springer US.

Collinge, W.O. et al., 2013. Dynamic life cycle assessment: framework and application to an institutional building. *The International Journal of Life Cycle Assessment*, 18(3), pp.538–552.

Çomaklı, K. & Yüksel, B., 2004. Environmental impact of thermal insulation thickness in buildings. *Applied Thermal Engineering*, 24(5-6), pp.933–940.

Çomaklı, K. & Yüksel, B., 2003. Optimum insulation thickness of external walls for energy saving. *Applied Thermal Engineering*, 23(4), pp.473–479.

Crawford, R.H., 2011. *Life Cycle Assessment in the Built Environment*, Taylor & Francis Ltd.

CURT, 2004. Collaboration, Integrated Information and the Project Lifecycle in Building Design, Construction and Operation. , p.14. Available at: http://codebim.com/wp-content/uploads/2013/06/CurtCollaboration.pdf.

Daly, H.E. & Cobb, J.B.J., 1989. *For The Common Good: Redirecting the Economy toward Community, the Environment, and a Sustainable Future*, Boston: Beacon Press.

Dana, J., 1838. On the Drawing of Figures of Crystals. *The American Journal of Science and Arts*, 33, pp.30–50.

Davis, D., 2013. *Modelled on Software Engineering : Flexible Parametric Models in the Practice of Architecture*. RMIT University.

Diefenbach, N., Cischinsky, H. & Rodenfels, M., 2010. *Datenbasis Gebäudebestand*, Available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/klima_altbau/Endbericht_Datenbasis.pdf.

van Dijk, H., Spiekman, M. & de Wilde, P., 2006. A monthly method for calculating energy performance in the context of European building regulations. In *Ninth International IBPSA Conference Montréal, Canada August 15-18, 2005*. pp. 255–262.

Dombaycı, Ö.A., 2007. The environmental impact of optimum insulation thickness for external walls of buildings. *Building and Environment*, 42(11), pp.3855–3859.

Eastman, C. et al., 1974. *An Outline of the Building Description System*, Research Report No. 50, Carnegie-Mellon Univ., Pittsburgh

Eastman, C., 1975. The Use of Computers Instead of Drawings in Building Design. *AIA Journal*, 63(3), pp.46–50.

Eberl, S., Mittermeier, P. & Hauser, G., 2014. Resource efficiency of buildins - A model for the assessment throughout the life cycle and implementation in a real case study. In *World Sustainable Building*. Barcelona, pp. 165 – 171.

Ebert, T., Essig, N. & Hauser, G., 2011. *Green Building Certification Systems*, Detail Green.

Economidou, M. et al., 2011. *Europe' s buildings under the microscope* B. Atanasiu et al., eds., Buildings Performance Institute Europe (BPIE).

Egger, M. et al., 2013. *BIM-Leitfaden für Deutschland*, Available at: papers3://publication/uuid/6A00173D-6403-4F0A-B19C-903574DCB724.

Ekkerlein, C., 2004. *Ökologische Bilanzierung von Gebäuden in frühen Planungsphasen auf Basis der Produktmodellierung*. Technische Universität München.

Elkington, J., 1994. Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development. *California Management Review*, 36, pp.90–100.

EU, 2010. *DIRECTIVE 2010/31/EU on the energy performance of buildings*, Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN.

Fahey, D.W. & Hegglin, M.I., 2010. *Twenty Questions and answers about the ozone Layer: 2010 update*, Available at: http://acdb-ext.gsfc.nasa.gov/Documents/O3_Assessments/Docs/WMO_2010/Q2_QA.pdf.

Fay, R., Treloar, G. & Iyer-Raniga, U., 2000. Life-cycle energy analysis of buildings: a case study. *Building Research & Information*, 28(1), pp.31–41.

Federal Register, 2009. *Executive Order 13514 "Federal Leadership in Environmental, Energy, and Economic Performance,"* United States. Available at: http://www.whitehouse.gov/assets/documents/2009fedleader_eo_rel.pdf\nhttp://www.whitehouse.gov/administration/eop/ceq/sustainability.

Finch, E.F., 1994. The uncertain role of life cycle costing in the renewable energy debate. *Renewable Energy*, 5, pp.1436–1443.

Finnveden, G., 2000. On the limitations of life cycle assessment and environmental systems analysis tools in general. *The International Journal of Life Cycle Assessment*, 5(4), pp.229–238.

Finnveden, G. & Lindfors, L., 1998. Data quality of life cycle inventory data—rules of thumb. *The International Journal of Life Cycle …*, 3(2), pp.65–66.

Finnveden, G. & Moberg, Å., 2005. Environmental systems analysis tools – an overview. *Journal of Cleaner Production*, 13(12), pp.1165–1173.

Finnveden, G. & Östlund, P., 1997. Exergies of natural resources in life-cycle assessment and other applications. *Energy*, 22(9), pp.923–931.

Flager, F. et al., 2012. Multi-objective building envelope optimization for life-cycle cost and global warming potential. In *eWork and eBusiness in Architecture, Engineering and Construction*. CRC Press, pp. 193–200.

Fleischer, G. & Schmidt, W.-P., 1997. Iterative screening LCA in an eco-design tool. *The International Journal of Life Cycle Assessment*, 2(1), pp.20–24.

Frenzel, C. & Hiller, M., 2014. TRNSYSLIZARD – Open Source Tool Für Rhinocerus – Grasshopper. In *Fifth German-Austrian IBPSA Conference*. pp. 490–496.

Frischknecht, R. & Büsser Knöpfel, S., 2013. *Ökofaktoren Schweiz 2013 gemäss der Methode der ökologischen Knappheit - Methodische Grundlagen und Anwendung auf die Schweiz*,

Fuchs, M. et al., 2013. *SNAP Systematik für Nachhaltigkeitsanforderungen in Planungswettbewerben - Endbericht*, Berlin.

Gazela, M. & Mathioulakis, E., 2001. A new method for typical weather data selection to evaluate long-term performance of solar energy systems. *Solar Energy*, 70(4), pp.339–348.

Global Footprint Network, 2009. *Ecological Footprint Standards*, Oakland. Available at: http://www.footprintnetwork.org/images/uploads/Ecological_Footprint_Standards_2009.pdf.

Goedkoop, M. et al., 2013. *ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation.*, Available at: http://www.pre-sustainability.com/download/misc/ReCiPe_main_report_final_27-02-2009_web.pdf.

Goedkoop, M. & Spriensma, R., 2001. *The Eco-Indicator 99 - A damage oriented method for Life Cycle Impact Asessment*, Available at: https://www.pre-sustainability.com/download/EI99_methodology_v3.pdf.

Graedel, T.E., 1998. *Streamlined Life-cycle Assessment*, Prentice Hall.

Graedel, T.E., 1996. Weighted matrices as product life cycle assessment tools. *The International Journal of Life Cycle Assessment*, 1(1), pp.85–89.

Guinée, J.B. et al., 2001. *Life Cycle Assessment: An Operational Guide to the ISO Standards - I: LCA in perspective*,

Hartwig, J., 2012. *Ökobilanz WoodCube Hamburg*,

Hasan, A., 1999. Optimizing insulation thickness for buildings using life cycle cost. *Applied Energy*, 63(2), pp.115–124.

Heeren, N. et al., 2015. Environmental Impact of Buildings—What Matters? *Environmental Science & Technology*, 49(16), pp.9832–9841.

Hegger, M. et al., 2012. *EcoEasy - Abschlussbericht*,

Hegger, M. et al., 2007. *Energie Atlas: Nachhaltige Architektur*, Birkhäuser.

Heijungs, R. & Huijbregts, M.A.J., 2004. A Review of Approaches to Treat Uncertainty in LCA. *Complexity and Integrated Resources Management. Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society*.

Hildebrand, L., 2012. Embodied energy in façade design. *Façade*, pp.64–75.

Hildebrand, L., 2014. *Strategic investment of embodied energy during the architectural planning process*. TU Delft.

Himburg, S., 2011. Energetische Bilanzierung von Wohngebäuden nach DIN V 18599. *Bauphysik*, 33(2), pp.99–110.

Hirschberger, H., Schween, R. & Schwarte, J., 1994. *Senkung der Baufolgekosten durch systematische und zustandsabhängige Erhaltung von Gebäuden und langzeitkostenoptimale Baustoffwahl*, Fraunhofer IRB Verlag.

Hochschorner, E. & Finnveden, G., 2003. Evaluation of two simplified Life Cycle assessment methods. *The International Journal of Life Cycle Assessment*, 8(3), pp.119–128.

Hollberg, A., Klüber, N., et al., 2016. A Method for Evaluating the Environmental Life Cycle Potential of Building Geometry. In *Sustainable Built Environment (SBE) regional conference*. Zurich, Switzerland.

Hollberg, A., Ebert, M., et al., 2016. Application of a parametric real-time LCA tool in students' design projects. In *Sustainable Built Environment*. Hamburg, pp. 72–81.

Hollberg, A. & Klüber, N., 2014. *Green Efficient Student Housing*, Weimar: Bauhaus-Universitätsverlag.

Hollberg, A. & Ruth, J., 2014. A Parametric Life Cycle Assessment Model for Facade Optimization. In *Building Simulation and Optimization*. London.

Hollberg, A. & Ruth, J., 2013. Facade optimization based on life cycle demands. In *8th Energy Forum on Advanced Building Skins.* Bressanone, Italy.

Hollberg, A. & Ruth, J., 2016. LCA in building design – A parametric approach. *International Journal of Life Cycle Assessment*, forthcomin.

Hoxha, E., 2015. *Amélioration de la fiabilité des évaluations environnementales des bâtiments*. Paris-Est.

Hoxha, E. et al., 2014. Method to analyse the contribution of material's sensitivity in buildings' environmental impact. *Journal of Cleaner Production*, 66, pp.54–64.

Huijbregts, M., 1998. Application of uncertainty and variability in LCA. *The International Journal of Life Cycle Assessment*, 3(5), pp.273–280.

Hunt, R.G. et al., 1998. Case studies examining LCA streamlining techniques. *The International Journal of Life Cycle Assessment*, 3(1), pp.36–42.

Hur, T. et al., 2005. Simplified LCA and matrix methods in identifying the environmental aspects of a product system. *Journal of Environmental Management*, 75(3), pp.229–237.

IBO, 2016. *OI3 Indikator - Leitfaden zur Berechnung von Ökokennzahlen für Gebäude*, Available at: http://www.ibo.at/de/documents/20160302_OI3_Berechnungsleitfaden_V3.1_001.pdf

IfLB, 1987. *Eigenheime Projektauswahl* Institut für Landwirtschaftliche Bauten, ed., Berlin: Bauakademie der DDR.

IPCC, 2013. *Fifth Assessment Report Climate Change 2013: The Physical Science Basis*,

IPCC, 2007. *IPCC Fourth Assessment Report: Climate Change 2007*,

ISO, 2009. DIN EN ISO 14040:2009 Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO.

IWES, 2012. *Windenergie Report Deutschland 2012*, Fraunhofer-Institut für Windenergie und Energiesystemtechnik.

Jakubiec, J.A. & Reinhart, C.F., 2011. Diva 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus. In *Proceedings of Building Simulation 2011, 12th Conference of International Building Performance Association*. Sydney, pp. 2202–2209.

Jelle, B.P., 2011. Traditional, state-of-the-art and future thermal building insulation materials and solutions - Properties, requirements and possibilities. *Energy and Buildings*, 43(10), pp.2549–2563.

Jens H. Liebchen, 2013. *Bau-Projekt-Management: Grundlagen und Vorgehensweisen*, Springer-Verlag.

John, V., 2012. *Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings*. ETH Zürich.

Jönsson, A., Björklund, T. & Tillman, A.-M., 1998. LCA of Concrete and Steel Building Frames. *The International Journal of Life Cycle Assessment*, pp.216–224.

JRC European commission, 2010a. *ILCD Handbook: Background document: Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment*,

JRC European commission, 2010b. *ILCD Handbook: Framework and Requirements for Life Cycle Impact Assessment Models and Indicators*,

JRC European commission, 2010c. *ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance*, Luxembourg: Publications Office of the European Union;

JRC European commission, 2011. *ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context*,

Kaelo, P. & Ali, M.M., 2006. Some variants of the controlled random search algorithm for global optimization. *Journal of Optimization Theory and Applications*, 130(2), pp.253–264.

Kägi, T. et al., 2016. Session "Midpoint, endpoint or single score for decision-making?"—SETAC Europe 25th Annual Meeting, May 5th, 2015. *The International Journal of Life Cycle Assessment*, 21(1), pp.129–132.

Kalusche, W., 2004. Technische Lebensdauer von Bauteilen und wirtschaftliche Nutzungsdauer eines Gebäudes.

Kellenberger, D. & Althaus, H.-J., 2009. Relevance of simplifications in LCA of building components. *Building and Environment*, 44(4), pp.818–825.

Kharrazi, A. et al., 2014. Advancing quantification methods of sustainability: A critical examination emergy, exergy, ecological footprint, and ecological information-based approaches. *Ecological Indicators*, 37, pp.81–89.

Khasreen, M.M., Banfill, P.F.G. & Menzies, G.F., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability*, 1(3), pp.674–701.

El Khouli, S., John, V. & Zeumer, M., 2014. *Nachhaltig Konstruieren* Detail Gre., Institut für Internationale Architektur-Dokumentation.

Klöpffer, W. & Grahl, B., 2014. *Life Cycle Assessment (LCA) - A guide to best practise*, Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.

Klöpffer, W. & Grahl, B., 2009. *Ökobilanz (LCA): Ein Leitfaden für Ausbildung und Beruf* 1. Auflage., Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.

Klüber, N., Hollberg, A. & Ruth, J., 2014. Life cycle optimized application of renewable raw materials for retrofitting measures. In *World Sustainable Building*. Barcelona.

König, H. et al., 2009. *Lebenszyklusanalyse in der Gebäudeplanung*, DETAIL.

König, H., De Cristofaro, L. & Löhnert, G., 2010. *Entwicklung von Bewertungsmaßstäben für das Bewertungssystem Nachhaltiger Wohnungsbau*,

Kounina, A. et al., 2013. Review of methods addressing freshwater use in life cycle inventory and impact assessment. *The International Journal of Life Cycle Assessment*, 18(3), pp.707–721.

Krozer, J. & Vis, J.C., 1998. How to get LCA in the right direction? *Journal of Cleaner Production*, 6(1), pp.53–61.

Kuhlman, T. & Farrington, J., 2010. What is Sustainability? *Sustainability*, 2(11), pp.3436–3448.

Lalit Narayan, R., Mallikarjuna Rao, K. & Sarcar, M.M.M., 2008. *Computer Aided Design and Manufacturing*, Prentice Hall of India.

Lasvaux, S. et al., 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. *The International Journal of Life Cycle Assessment*, 20(11), pp.1473–1490.

Lasvaux, S. & Gantner, J., 2013. Towards a new generation of building LCA tools adapted to the building design process and to the user needs? In *Sustainable Building*. Graz, pp. 406–417.

Lasvaux, S., Gantner, J. & Saunders, T., 2012. *Requirements for building LCA tool developers*, Available at: http://www.eebguide.eu/eebblog/wp-content/uploads/2012/12/D-4.3.-Requirements-for-Building-LCA-tool-designer.pdf.

Lawson, B., 1994. *Design in Mind*, Butterworth Architecture.

Lawson, B., 2006. *How designers think: the design process demystified* 4th editio., Elsevier/Architectural Press.

Lee, G., Sacks, R. & Eastman, C.M., 2006. Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in Construction*, 15(6), pp.758–776.

Leontief, W.W., 1951. *Input-Output Economics*. In New York: Oxford University Press.

Lewandowska, A. et al., 2014. Between full LCA and energy certification methodology—a comparison of six methodological variants of buildings environmental assessment. *The International Journal of Life Cycle Assessment*, 20(1), pp.9–22.

Lichtenheld, T., Hollberg, A. & Klüber, N., 2015. Echtzeitenergieanalyse für den parametrischen Gebäudeentwurf. In *Bauphysiktage Kaiserslautern*. Kaiserslautern: Technische Universität Kaiserslautern.

Lützkendorf, T. et al., 2015. Net-zero buildings: incorporating embodied impacts. *Building Research & Information*, 43(1), pp.62–81.

Madetoja, E. et al., 2008. Visualizing multi-dimensional pareto-optimal fronts with a 3D virtual reality system. *Proceedings of the International Multiconference on Computer Science and Information Technology, IMCSIT 2008*, 3, pp.907–913.

Manfredi, S. et al., 2012. *Product Environmental Footprint (PEF) Guide*, Available at: http://ec.europa.eu/environment/archives/eussd/pdf/footprint/PEF methodology final draft.pdf.

Mcdonough, W. & Braungart, M., 2002. *Cradle to Cradle: Remaking the Way We Make Things*, San Val.

Meex, E., Knapen, E. & Verbeeck, G., 2016. User-friendliness of current building environmental impact assessment tools: an architect's perpective. In *Sustainable Built Environment*. Hamburg, pp. 1306–1315.

Menges, A. & Ahlquist, S., 2011. *Computational Design Thinking*, Wiley.

Minergie, 2016. Berechnung der Grauen Energie bei MINERGIE-A®, MINERGIE-ECO®, MINERGIE-P-ECO® UND MINERGIE-A-ECO® BAUTEN. , pp.1–12. Available at: https://www.minergie.ch/tl_files/download/Nachweistools/Minergie-Eco 2016/1004-1_22_60201_Berechnung_Graue_Energie_online_2016_V1.1.pdf.

Mithraratne, N., Vale, B. & Vale, R., 2007. *Sustainable Living: the Role of Whole Life Costs and Values*, Routledge.

Molina, M.J. & Rowland, F.S., 1974. Stratospheric sink for chlorofluoromethanes: chlorine atomc-atalysed destruction of ozone. *Nature*, 249, pp.810–812.

Molter, K. & Linnemann, M., 2010. *Wärmedämmverbundsystem und das verlorene Ansehen der Architektur*, Kaiserslautern.

Morbitzer, C. et al., 2001. Integration of Building Simulation into the Design Process of an Architecture Pratice. In *Building Simulation (IBPSA)*. Rio de Janeiro, Brazil, pp. 697–704.

NATSPEC, 2013. *BIM and LOD - Building Information Modelling and Level of Development.*,

Negendahl, K., 2015. Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction*, 54, pp.39–53.

Neuberg, F., 2004. *Ein Softwarekonzept zur Internet-basierten Simulation des Ressourcenbedarfs von Bauwerken*. Technische Universität München.

Oers, L. Van et al., 2002. *Abiotic resource depletion in LCA*, Available at: http://media.leidenuniv.nl/legacy/report abiotic resource depletion.pdf.

Ostad-Ahmad-Ghorabi, H., 2010. *Parametric Ecodesign Assessment into Computer Aided Design*, Südwestdeutscher Verlag für Hochschulschriften.

Ostad-Ahmad-Ghorabi, H. & Collado-Ruiz, D., 2011. Tool for the environmental assessment of cranes based on parameterization. *International Journal of Life Cycle Assessment*, 16(5), pp.392–400.

Ostermeyer, Y., Wallbaum, H. & Reuter, F., 2013. Multidimensional Pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*, 18(9), pp.1762–1779.

Ozel, M., 2011. Thermal performance and optimum insulation thickness of building walls with different structure materials. *Applied Thermal Engineering*, 31(17-18), pp.3854–3863.

Pasanen, P., 2015. State of the Art in Building Life-Cycle Assessment: One Click LCA. *White paper*, pp.1–3.

Passer, A. et al., 2015. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. *The International Journal of Life Cycle Assessment*, 20(9), pp.1199–1212.

Paulson Jr., B.C., 1976. Designing to Reduce Construction Costs. *Journal of the Construction Division*, 102(4), pp.587–592.

Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, 31(1), pp.55–71.

Petersen, S. & Svendsen, S., 2010. Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings*, 42(7), pp.1113–1119.

Peuportier, B. & Putzeys, K., 2005. Inter-Comparison and Benchmarking of LCA-Based Environmental Assessment and Design Tools. *PRESCO*, p.74. Available at: http://www.etn-presco.net/generalinfo/index.html.

Pfeiffer, M. & Arlt, J., 2005. *Lebensdauer der Baustoffe und Bauteile zur Harmonisierung der wirtschaftlichen Nutzungsdauer im Wohnungsbau*, Fraunhofer IRB Verlag.

Picco, M., Lollini, R. & Marengo, M., 2014. Towards energy performance evaluation in early stage building design: A simplification methodology for commercial building models. *Energy and Buildings*, 76, pp.497–505.

Pintér, J. & Weisstein, E.W., 2015. Evolution Strategies. *MathWorld--A Wolfram Web Resource.* Available at: http://mathworld.wolfram.com/EvolutionStrategies.html.

Redclift, M., 2005. Sustainable Development (1987–2005): An Oxymoron Comes of Age. *Sustainable Development*, 13(July), pp.212–227.

Reitschmidt, G. & Díaz, J., 2015. Automatisierte Ökobilanzierung der Herstellungsphase von Gebäuden bei Verwendung von Building Information Modeling. In *Conference Proceedings of the 10th Energy Forum*. Bern, pp. F5–5.

Rittel, H., 1970. Der Planungsprozess als iterativer Vorgang von Varietätserzeugung und Varietätseinschränkung. *Arbeitsberichte zur Planungsmethodik 4 Entwurfsmethodik in der Bauplanung*, pp.75–92.

Rittel, H.W., 1992. *Planen, Entwerfen, Design: Ausgewählte Schriften zu Theorie und Methodik* W. D. Reuter, ed., Stuttgart: W. Kohlhammer GmbH.

Rittel, H.W.J. & Webber, M.M., 1973. Dilemmas in a General Theory of Planning. *Policy Sciences*, 4, pp.155–169.

Ritter, F., 2011. *Lebensdauer von Bauteilen und Bauelementen*, Technische Universität Darmstadt, Institut für Massivbau.

Ritthoff, M., Rohn, H. & Liedtke, C., 2002. *Calculating MIPS : resource productivity of products and services*, Available at: http://epub.wupperinst.org/frontdoor/index/index/docId/1577.

Roudsari, M.S., Smith, A. & Gill, G., 2013. Ladybug: A parametric Environmental Plugin for Grasshopper to held designers environmentally conscious design. In *Building Simulation (IBPSA)*. Chambéry, France, pp. 3128–3135.

Rowe, P.G., 1987. *Design Thinking*, MIT Press.

Sakulpipatsin, P. et al., 2010. An exergy application for analysis of buildings and HVAC systems. *Energy and Buildings*, 42(1), pp.90–99.

Schlueter, A. & Thesseling, F., 2009. Building information model based energy/exergy performance assessment in early design stages. *Automation in Construction*, 18(2), pp.153–163.

Schmidt, A.C. et al., 2004. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. *The International Journal of Life Cycle Assessment*, 9(2), pp.122–129.

Schneider, C., 2011. *Steuerung der Nachhaltigkeit im Planungs- und Realisierungsprozess von Büro- und Verwaltungsgebäuden*,

Schuurmans-stehmanna, A.M., 1994. Environmental life cycle analysis of construction products with and without recycling. *Studies in Environmental Science*, 60(Proceeding of the International Conference on Environmental Implications of Construction Materials and Technology Developments), pp.709–711.

Seo, S., Tucker, S. & Newton, P., 2007. Automated Material Selection and Environmental Assessment in the Context of 3D Building Modelling. *Journal of Green Building*, 2(2), pp.51–61.

Silvestre, J.D. et al., 2015. NativeLCA - a systematic approach for the selection of environmental datasets as generic data: application to construction products in a national context. *The International Journal of Life Cycle Assessment*, pp.731–750.

Simon, H.A., 1996. *The sciences of the artificial (third edition)* Third edit., MIT Press.

de Souza, C.B., 2009. A critical and theoretical analysis of current proposals for integrating building thermal simulation tools into the building design process. *Journal of Building Performance Simulation*, 2(4), pp.283–297.

Stahel, W.R. & Reday-Mulvey, G., 1977. *The potential for substituting manpower for energy* Rsearch co., Commission of the European Communities.

Stolte, C. et al., 2013. Auswertung von Verbrauchskennwerten energieeffizient sanierter Wohngebäude. Begleitforschung zum dena-Modellvorhaben Effizienzhäuser. , pp.1–19.

Stover, C. & Weisstein, E.W., 2015. Parametric Equations. Available at: http://mathworld.wolfram.com/ParametricEquations.html.

Sutherland, I.E., 1963. *Sketchpad a Man-Machine Graphical Communication System*. Massachusetts Institute of Technology.

Szalay, A. & Zöld, Z., 2007. What is missing from the concept of the new European Building Directive? *Building and Environment*, 42, pp.1761–1769.

Szalay, Z. et al., 2014. Life Cycle Based Optimization of Building Design. In *World Sustainable Building*. Barcelona, pp. 17–23.

Teresko, J., 1993. Parametric Technology Corp.: Changing the way Products are Designed. *Industry Week*, (20 December).

Udo de Haes, H., 1996. Towards a methodology for life cycle impact assessment. *SETAC-Europe, Brussels, Belgium*.

UNEP, 2011. *Towards a Life Cycle Sustainability A ssessment: Making informed choices on products*, United Nations Environmental Program.

UNEP SBCI, 2009. *Buildings and Climate Change Summary for Decision-Makers*, Sustainable Buildings & Climate Initiative

US EPA, 2015. What is Sustainability? Available at: http://www2.epa.gov/sustainability/learn-about-sustainability#what.

UVEK & BAFU, 2008. *Die Methode der Umweltbelastungspunkte*, Available at: http://www.biovision.ch/fileadmin/pdf/d/CLEVER/Ergaenzende_Lehrmittel/Methode_Umweltbelastungspunkte.pdf.

Wastiels, L., Delem, L. & Dessel, J. Van, 2014. To Module D or not to Module D? The relevance and difficulties of considering the recycling potential in building LCA. In *World Sustainable Building*. Barcelona.

Weicker, K., 2002. *Evolutionäre Algorithmen*, Springer.

Weisberg, D.E., 2008. The Engineering Design Revolution - The People, Companies and Computer Systems That Changed Forever the Practice of Engineering. Available at: http://www.cadhistory.net/.

Weißenberger, M., Jensch, W. & Lang, W., 2014. The convergence of life cycle assessment and nearly zero-energy buildings : The case of Germany. *Energy & Buildings*, 76, pp.551–557.

Weitz, K.A. et al., 1996. Considerations and a report on the state of practice. *The International Journal of Life Cycle Assessment*, 1(2), pp.79–85.

Wenzel, H., 1998. Application dependency of lca methodology: Key variables and their mode of influencing the method. *The International Journal of Life Cycle Assessment*, 3(5), pp.281–288.

Weytjens, L. et al., 2011. The "Architect-friendliness" Of Six Building Performance Simulation Tools: A Comparative Study. *International Journal of Sustainable Building Technology and Urban Development*, 2(3), pp.237–244.

Weytjens, L., Verbeeck, G. & Verdonck, E., 2009. Classification and Use of Design Tools: The Roles of Tools in the Architectural Design Process. *Design Principles and Practices: An International Journal*, 3(1), pp.289–302.

Wittstock, B. et al., 2012. *EeBGuide Guidance Document Part B: BUILDINGS*,

Wittstock, B. et al., 2009. Gebäude aus Lebenszyklusperspektive − Ökobilanzen im Bauwesen. *Bauphysik*, 31.

Woodbury, R., 2011. *Elements of Parametric Design*, Routledge.

Zabalza Bribián, I., Aranda Usón, A. & Scarpellini, S., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, 44(12), pp.2510–2520.

Standards

ISO 13790:2008 - Energy performance of buildings -- Calculation of energy use for space heating and cooling. International Organisation for Standardisation. Geneva.

ISO 14040:2009 Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen. International Organisation for Standardisation. Geneva.

ISO 14044:2006 Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen. International Organisation for Standardsation. Geneva.

ISO 10456:2010 Baustoffe und Bauprodukte – Wärme- und feuchtetechnische Eigenschaften – Tabellierte Bemessungswerte und Verfahren zur Bestimmung der wärmeschutztechnischen Nenn- und Bemessungswerte. International Organisation for Standardisation. Geneva.

ISO 15686-8:2008 Buildings and constructed assets - Service-life planning - Part 8: Reference service life and service-life estimation. International Organisation for Standardisation. Geneva.

EN 15643-1:2010 Nachhaltigkeit von Bauwerken – Bewertung der Nachhaltigkeit von Gebäuden – Teil 1: Allgemeine Rahmenbedingungen. European Commitee for Standardization. CEN/TC 350.

EN 15643-2:2011 Nachhaltigkeit von Bauwerken – Bewertung der Nachhaltigkeit von Gebäuden – Teil 2: Rahmenbedingungen für die Bewertung der umweltbezogenen Qualität. European Commitee for Standardization. CEN/TC 350.

EN 15804:2012 Nachhaltigkeit von Bauwerken – Umweltproduktdeklarationen – Grundregeln für die Produktkategorie Bauprodukte. European Commitee for Standardization. CEN/TC 350.

EN 15978:2012 Nachhaltigkeit von Bauwerken – Bewertung der umweltbezogenen Qualität von Gebäuden. European Commitee for Standardization. CEN/TC 350.

DIN 4108:2003 - Wärmeschutz und Energieeinsparung in Gebäuden. Deutsches Institut für Normung.

DIN 4108-4:2003 Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 4: Wärme- und feuchteschutztechnische Bemessungswerte. Deutsches Institut für Normung.

DIN V 18599-1:2011 Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwasser und Beleuchtung - Teil 1: Allgemeine Bilanzierungsverfahren, Begriffe, Zonierung und Bewertung der Energieträger. Deutsches Institut für Normung.

DIN V 18599-2:2011 Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwasser und Beleuchtung - Teil 2: Nutzenergiebedarf für Heizen und Kühlen von Gebäudezonen. Deutsches Institut für Normung.

DIN V 18599-10:2011 Energetische Bewertung von Gebäuden – Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung – Teil 10: Nutzungsrandbedingungen, Klimadaten. Deutsches Institut für Normung.

DIN V 4701-10:2003 Energetische Bewertung heiz- und raumlufttechnischer Anlagen – Teil 10: Heizung, Trinkwassererwärmung, Lüftung. Deutsches Institut für Normung.

DIN V 4701-10:2007 Beiblatt 1 Energetische Bewertung heiz- und raumlufttechnischer Anlagen – Teil 10: Heizung, Trinkwassererwärmung, Lüftung; Beiblatt 1: Anlagenbeispiele. Deutsches Institut für Normung.

SIA 2032:2012 Graue Energie von Gebäuden. Schweizerischer Ingenieur- und Architektenverein. Zurich.

SIA 2040:2011. SIA - Effizienzpfad Energie. Schweizerischer Ingenieur- und Architektenverein. Zurich.

Glossary

Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 14040:2009, p.10)
Average data	Data representative of a product, product group or construction service, provided by more than one supplier (EN 15804:2012, p.7)
Category indicator	Quantifiable representation of an impact category (ISO 14040:2009, p.13)
Characterization factor	Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator (ISO 14040:2009, p.12)
Cut-off criteria	Specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or a product system to be excluded from a study (ISO 14040:2009, p.10)
Declared unit	Quantity of a building product for use as a reference unit in an EPD for an environmental declaration based on one or more information modules (EN 15804:2012, p.7)
Elementary flow	Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation (ISO 14040:2009, p.9)
Embodied impact	Environmental impact caused by construction and deconstruction of a building, including the replacement of building components
Environmental indicator	Quantifiable value related to environmental impacts or aspects (EN 15978:2012, p.10)
Environmental impact	Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g. emissions, resource extraction, land use). (JRC European commission 2010b) Change to the environment, whether adverse or beneficial, wholly or partially, resulting from environmental aspects (EN 15978:2012, p.8)

Environmental Product Declaration	An EPD is a standardized and LCA based tool to communicate the environmental performance of a product or system, and is applicable worldwide for all interested companies and organizations (http://www.environdec.com/)
Final energy	Final energy is the energy which the consumer buys or receives.
Functional unit	Quantified performance of a product system for use as a reference unit (ISO 14040:2009, p.10)
Generic data	A generic data set has been developed using at least partly other information then those measured for the specific process. This other information can be stoichiometric or other calculation models, patents and other plans for processes or products, expert judgement etc. (JRC European commission 2010c, p.246)
Impact category	Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO 14040:2009, p.13)
Life cycle assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2009, p.7)
Life cycle costing	Life cycle costing, or LCC, is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance and disposal. (UNEP/SETAC, 2009)
Life cycle impact	Total environmental impact caused by a building throughout its life cycle
Life cycle impact assessment	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 14040:2009, p.7)
Life cycle inventory analysis	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14040:2009, p.7)
Life cycle sustainability assessment	Life cycle sustainability assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle (UNEP 2011, p.3)
Operational impact	Environmental impact caused by the operational energy demand of a building

Primary energy	Primary energy is the energy as it is available in the natural environment, i.e. the primary source of energy
Product category rules	Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories (EN 15804:2012, p.9)
Reference service life	Service life of a building product that is known to be expected under a particular set (i.e. a reference set) of in-use conditions, and which may form the basis for estimating the service life under other in-use conditions (EN 15804:2012, p.10)
Reference study period	Period over which the time-dependent characteristics of the object of assessment are analysed (EN 15978:2012, p.11)
Specific data	Data representative of a product, product group or construction service, provided by one supplier (EN 15804:2012, p.10)
System boundary	Interface in the assessment between a building and its surroundings or other product systems (EN 15978:2012, p.12)
Useful energy	Useful energy or delivered energy is the amount of energy which is an input in an end-use application

Summary

The building sector is responsible for a large share of environmental impacts, including energy and recource demand, greenhouse gas emissions, and waste. Architects and planners define the environmental impacts that a building will have over the next fifty or one hundred years to a great extent. Therefore, they are the key players for reducing the environmental impacts of buildings. *Life Cycle Assessment* (LCA) is a useful method to holistically analyse the environmental impact of a building. However, it is currently not employed to improve the environmental performance of building designs. One main reason is the lack of an adequate method for application of LCA in the architectural design process. Therefore, the main objective of this thesis is to provide architects and planners with a method for environmental building design optimization in the design process. The main research question corresponding to this objective is:

> Which method enables architects to environmentally optimize a building in the design process?

This research question can be divided into four sub-questions which correspond to the four parts of the thesis (see Figure 52).

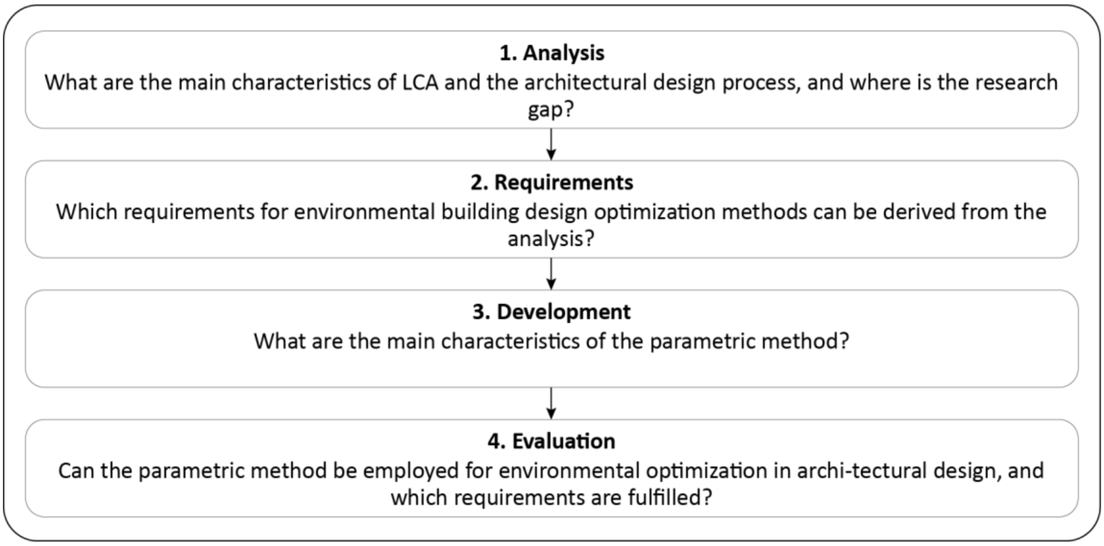

Figure 52: Sub-research questions

The research approach is based on these questions and consists of four main steps:

1. an analysis based on a literature review including the state of the art of LCA for buildings, the common stages of the architectural design process in relation to LCA and the research gap of current LCA tools for buildings;

2. establishment of requirements for environmental building design optimization methods based on the analysis;
3. development of a parametric method for building design optimization based on LCA;
4. evaluation of the method developed for this thesis using three examples of application and the established requirements

The following summaries describe the key findings for each of the four chapters provide the answers to the sub-research questions.

Chapter 1:

An analysis of currently available methods for environmental system analysis indicates that LCA is most suitable for the evaluation of environmental sustainability of buildings. LCA analyses inputs, outputs, and environmental impact throughout the whole life cycle. Regulations for the application of LCA for buildings exist, and environmental data is becoming increasingly available, for example in the form of databanks or environmental product declarations (EPDs).

The architectural design process usually consists of six main stages. Decisions made in the early stages of the design process, namely stages 1 and 2, have the greatest influence on environmental impacts. As such, design optimization is best achieved in these stages. The dilemma inherent to LCA in the design process is that decisions taken in stage 2 have the greatest influence, but information is scarce and uncertain. Information needed for a complete LCA is usually only available after stage 4. By then the LCA results are less useful, because making significant changes at this stage is too costly. Basically, once the necessary information is available, the LCA results are impractical to implement.

The challenges for the integration of LCA in the design process include short deadlines in the design process, the uniqueness of buildings, and the lack of practical tools, amongst others. Numerous tools for LCA and energy analysis for buildings exist. An analysis of these tools indicates that they are either very complex but holistic, such as generic LCA tools, BIM, Legep, and academic approaches, or simple but not holistic, such as spreadsheet-based tools and online catalogues. Furthermore, none of them provide the opportunity for optimization in the architectural design process, which is the main research gap.

Chapter 2:

The requirements derived from the analysis have been summarized in the form of a catalogue consisting of eight mandatory and six optional requirements. The mandatory requirements aim for guaranteeing a minimum quality of results and a minimum applicability in architectural practice. The optional requirements are recommendations to further improve the applicability. The catalogue can be used for both the evaluation of existing methods and as a guideline for the development of new environmental building design optimization methods. If a method does not fulfil all mandatory requirements, it cannot be regarded as suitable for application in the design process. The existing commercial tools analysed in Chapter 1 do not provide a closed workflow and therefore do not fulfil the mandatory requirement for optimization. The academic approaches analysed are not publicly available and no declaration of the time needed for application could be found in the literature. As such, it is not possible to evaluate them using the catalogue. In this thesis, the catalogue serves as a guideline for the development of a parametric method in Chapter 3 and its evaluation in Chapter 4.

Chapter 3:

The key element of the method called *Parametric Life Cycle Assessment* (PLCA) is a digital, parametric LCA model. The workflow for using the model can be divided into four steps: input, calculation, output, and optimization (see Figure 53). The unique and most important characteristic of the model is that all four steps and all components within those steps are interlinked and form a closed calculation loop. This provides the basis for optimization.

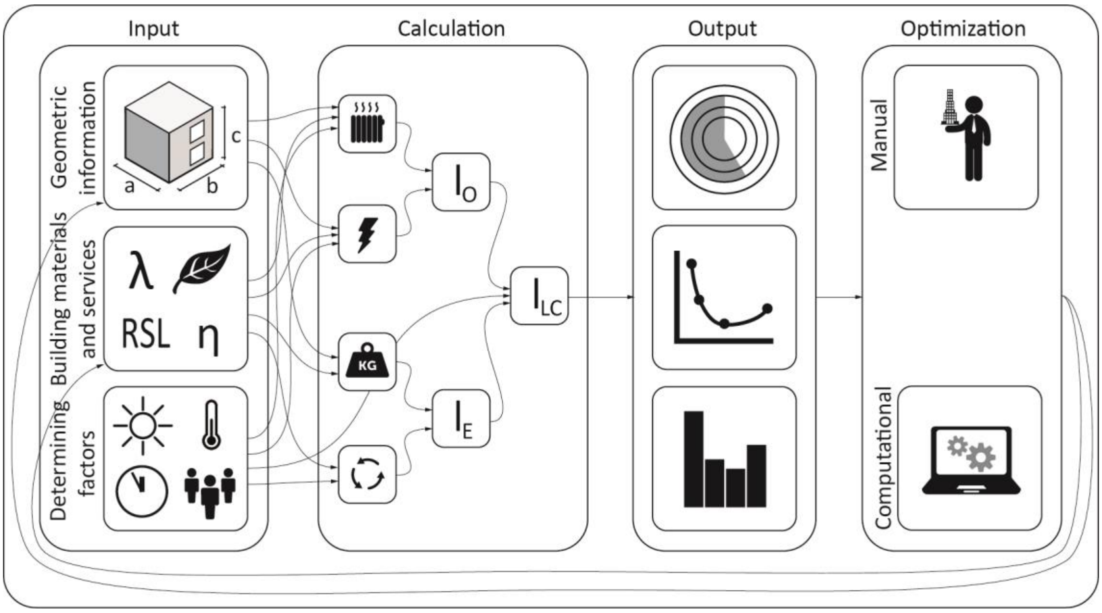

Figure 53: Schematic structure of the workflow of PLCA

The basic prerequisite for the parametric model is the parametrization of all input. The input consists of *geometry*, *building materials and services*, and *determining factors*. The geometry is input by either drawing a 3D model which is parametrized or by directly defining it parametrically. A combined database for building materials and services containing all necessary data was established and linked to the model. The determining factors are also defined parametrically. The energy demand calculation is implemented within the calculation step to avoid the exporting and importing necessary when using conventional approaches. Based on the algorithms developed, the whole life cycle impact is calculated and output. Various possibilities for visualization of the LCA results are provided. Using this self-contained workflow, the architect can either quickly generate variants manually to iteratively improve a building design or employ computational optimizers.

Chapter 4:

The parametric method was applied in three different examples, each with a different focus. The first example shows that PLCA is applicable for building material optimization using computational optimizers. Within a short time period of 15 minutes, the optimum within a search space of more than 300 million possible solutions was found. The second example presents the potential that PLCA offers for geometry optimization using a semi-automatic approach in early design stages. Based on a set of assumptions, LCA could be calculated before information about building materials and services is available. In the third example, nine students employed PLCA for combined manual optimization of material and geometry. The comparison of results to a reference group indicates that a reduction in environmental impact of 40% was possible using PLCA. These examples also served to evaluate PLCA based on the requirement catalogue. All mandatory and all but one optional requirements have been fulfilled. In all examples the environmental impact could be significantly reduced. The comparison with current available approaches indicates that PLCA is much more time-efficient, while providing at least the same accuracy of results.

Conclusion and outlook

By minimizing the effort of performing LCA for buildings and incorporating it into the design process, PLCA allows architects to focus on the main task of designing the building. Furthermore, the building design can be time-efficiently optimized from the beginning of the most influential early design stages, which has not been possible until now. Due to its flexibility, PLCA provides a good starting point for further research. In the future, uncertainty information on the input parameters could be used to identify robust solutions. These represent designs that might not achieve the optimum using mean values, but perform well in all cases, including best and worst case scenarios. Furthermore, PLCA could be extended by integrating further analyses and social and economic aspects of sustainability. As the world's population is growing and resources are becoming scarcer, sustainability will become even more important in the future. Architects and planners have a great potential to enhance sustainability in the building sector. Applying PLCA in the design process today is one step towards more environmentally friendly buildings.

Zusammenfassung

Der Gebäudesektor ist weltweit für einen großen Teil an negativen Umweltwirkungen verantwortlich, zu denen unter anderem Energie- und Ressourcenverbrauch sowie Treibhausgas- und Schadstoffemissionen zählen. Architekten und Planer beeinflussen in einer Planungszeit von einigen Monaten maßgeblich die Umweltwirkungen, die ein Gebäude innerhalb der nächsten 50 oder 100 Jahre verursachen wird. Im Gegensatz zu Fachplanern sind Architekten meist bereits von Beginn der frühen Phasen, bei denen das Optimierungspotential am größten ist, an der Planung beteiligt. Daher haben sie die Möglichkeit die Umweltwirkungen von Gebäuden deutlich zu reduzieren. Die Ökobilanzierung (engl. Life Cycle Assessment, LCA) ermöglicht es, Gebäude ganzheitlich für den gesamten Lebenszyklus ökologisch zu bewerten und sie wird unter anderem für die Nachhaltigkeitszertifizierung von Gebäuden genutzt. Allerdings wird sie aufgrund ihrer Komplexität zurzeit nicht im architektonischen Entwurfsprozess angewendet, obwohl hier das größte Potential besteht die Umweltwirkungen zu optimieren. Ein wesentlicher Grund sind fehlende praktikable Methoden im architektonischen Entwurfsprozess. Daher besteht das Hauptziel der vorliegenden Arbeit in der Entwicklung einer Methode, die es ermöglicht, Gebäude im Entwurfsprozess zeiteffizient ökologisch zu optimieren. Aus diesem Ziel ergibt sich die Forschungsfrage:

> Welche Methode ermöglicht Architekten die ökologische Optimierung von Gebäuden im Entwurfsprozess?

Die Forschungsfrage kann in vier Teilfragen gegliedert werden, die den vier Kapiteln dieser Arbeit entsprechen (siehe Abbildung 1).

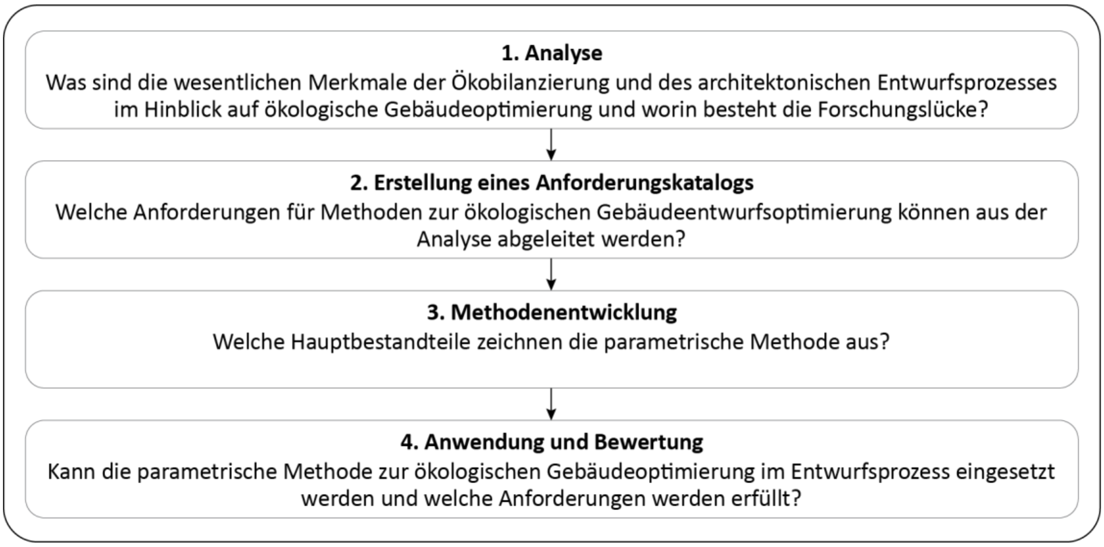

Abbildung 1: Gliederung der Forschungsfrage

Der Forschungsansatz baut auf diesen Fragen auf und gliedert sich daher in vier Schritte, die in vier Kapiteln behandelt werden. Kapitel 1 stellt eine umfassende Literaturrecherche zum Stand der Technik im Bereich Gebäudeökobilanzierung und des architektonischen Entwurfsprozesses im Hinblick auf ökologische Gebäudeoptimierung dar. Darüber hinaus werden Forschungslücken bestehender Ansätze analysiert. Basierend auf dieser Analyse wird in Kapitel 2 ein Anforderungskatalog für Methoden zur ökologischen Optimierung von Gebäuden im Entwurfsprozess erstellt. Mit Hilfe dieses Anforderungskatalogs wird in Kapitel 3 eine parametrische Methode zur ökologischen Optimierung von Gebäuden auf Basis der Ökobilanzierung entwickelt. Der Hauptansatz besteht dabei in der Kombination der Prinzipien des parametrischen Entwerfens mit der Methode der Ökobilanzierung. Um die neuartige Methode zu testen, wird sie in Kapitel 4 in drei Beispielen für die Optimierung von Gebäudeentwürfen angewendet. Abschließend erfolgt eine Bewertung der Methode mit Hilfe des in Kapitel 2 entwickelten Anforderungskatalogs.

Die folgenden Zusammenfassungen der Kapitel bieten jeweils einen Überblick über die wesentlichen Erkenntnisse und geben Antworten auf die vier Forschungsfragen.

Kapitel 1: Analyse

Der Vergleich aktueller Methoden zur ökologischen Bewertung von Produkten zeigt, dass sich die Methode der Ökobilanzierung für Gebäude am besten eignet. Die Ökobilanzierung analysiert Inputs, Outputs und Umweltwirkungen über den gesamten Lebenszyklus des Gebäudes, inklusive Herstellung, Betrieb, Austausch und Entsorgung. Im Gegensatz zu anderen Methoden stehen Richtlinien und Normen für die Anwendung der Ökobilanzierung für Gebäude zur Verfügung.

Um die Ökobilanzierung in Bezug zum architektonischen Entwurfsprozess zu setzen, wurde dieser in sechs typische Phasen unterteilt. Entscheidungen, die in frühen Phasen (Phase 1 und 2) getroffen werden, haben den größten Einfluss auf die Umweltwirkungen des Gebäudes. Daher ist in diesen Phasen das Optimierungspotential am größten. Allerdings stehen die für die Ökobilanzierung nötigen Informationen, wie genaue Materialspezifikationen, oft nur nach Entwurfsphase 4 zur Verfügung. Zu diesem Zeitpunkt wurden große Teile der Entwurfsentscheidungen schon getroffen und wesentliche Änderungen sind zu teuer, weshalb die Ökobilanzergebnisse nur begrenzt von Nutzen sind. Das Dilemma der Anwendung der Ökobilanzierung während des Entwurfsprozesses besteht daher darin, dass die Ergebnisse keinen Einfluss mehr haben, sobald alle nötigen Informationen bekannt sind.

Die Analyse bestehender Ansätze zur Ökobilanzierung von Gebäuden zeigte, dass diese zwei maßgebliche Schwachstellen aufweisen. Einerseits sind ganzheitliche Programme, wie generische Ökobilanzierungstools, Legep, BIM-basierte Ansätze und akademische Lösungen, zu komplex für die Anwendung im Entwurfsprozess. Andererseits sind einfache Programme, wie tabellarische Anwendungen und Online-Bauteilkataloge, nicht ganzheitlich und damit ungeeignet. Des Weiteren bietet keines dieser Werkzeuge die Möglichkeit für eine Entwurfsoptimierung auf Basis der Ökobilanz, was eine wesentliche Forschungslücke darstellt.

Kapitel 2: Erstellung eines Anforderungskatalogs

Die Anforderungen, die sich aus der Analyse ergaben, wurden in einem Katalog zusammengefasst, der sowohl als Grundlage für die Entwicklung neuer Methoden als auch zur Bewertung bestehender Methoden dienen kann. Der Katalog besteht aus acht Pflichtanforderungen zur Sicherstellung einer Mindestqualität der Ergebnisse und der Praxistauglichkeit und sechs optionalen Empfehlungen zur weiteren Verbesserung der Anwendbarkeit. Wenn eine getestete Methode nicht alle verpflichtenden Anforderungen erfüllt, kann sie nicht als tauglich für die Anwendung während des Entwurfsprozesses erachtet werden. In dieser Arbeit dient der eigens entwickelte Katalog sowohl als Leitfaden zur Entwicklung der parametrischen Methode in Kapitel 3 als auch zur Bewertung dieser in Kapitel 4.

Kapitel 3: Methodenentwicklung

Das zentrale Element der parametrischen Methode zur ökologischen Optimierung von Gebäudeentwürfen – *Parametric Life Cycle Assessment* (PLCA) – ist ein digitales, parametrisches Ökobilanzmodell. Der Ablauf der Anwendung dieses Modells kann in vier Schritte unterteilt werden: Eingabe, Berechnung, Ausgabe und Optimierung (siehe Abbildung 1).

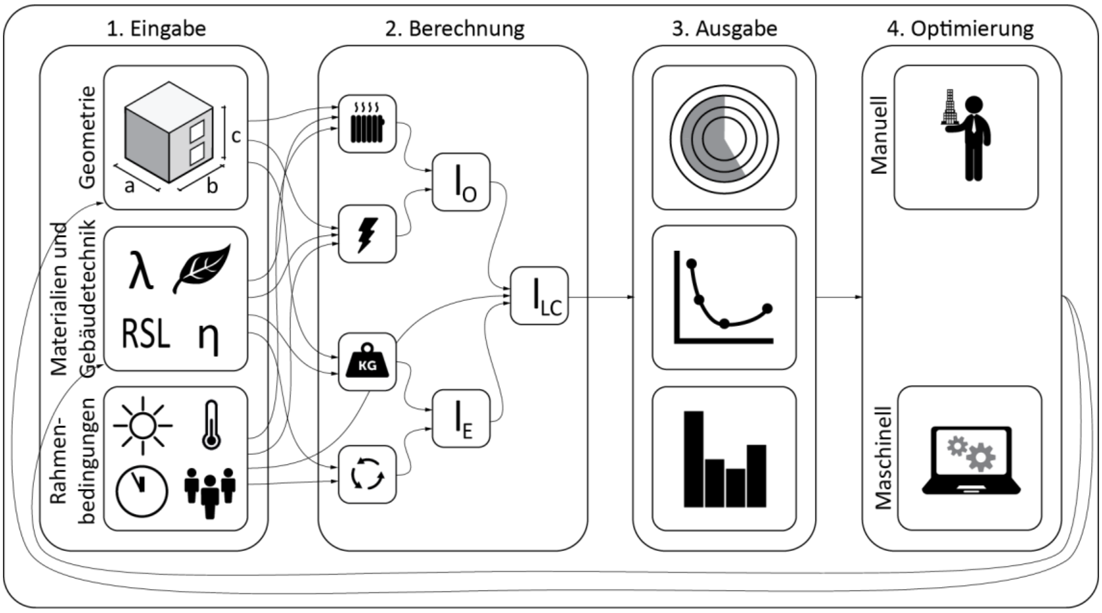

Abbildung 2: Ablaufschema von PLCA

Die grundlegende Anforderung zur Anwendung des Modells ist die Parametrisierung aller Eingangsgrößen. Diese bestehen aus drei Arten von Informationen: Erstens Geometrie, zweitens Baumaterialien und Gebäudetechnik und drittens Randbedingungen. Die Geometrie wird entweder über ein 3D Modell eingegeben, das anschließend parametrisiert wird oder direkt parametrisch definiert. Eine kombinierte Datenbank mit allen nötigen Informationen zu physikalischen Eigenschaften, ökologischen Kennwerten und Lebensdauerdaten wurde in dieser Arbeit erstellt und mit dem Modell verknüpft. Randbedingungen wie Betrachtungszeitraum oder Nutzungsszenarien werden ebenfalls parametrisch definiert. Die Berechnung des Energiebedarfs im Gebäudebetrieb ist komplett in den zweiten Schritt der Berechnung integriert, damit kein Im- und Export von Teilergebnissen wie bei herkömmlichen Ansätzen nötig ist. Auf Basis der in dieser Arbeit entwickelten Algorithmen werden die Umweltwirkungen über den gesamten Lebenszyklus ermittelt und ausgegeben. Dieser in sich geschlossene Ablauf stellt die Grundlage für den Optimierungsprozess dar. Architekten können mit Hilfe des parametrischen Ansatzes manuell Varianten generieren und iterativ die Umweltwirkungen des Entwurfes reduzieren oder computergestützte Optimierer anbinden.

Kapitel 4: Anwendung und Bewertung

Die hier entwickelte parametrische Methode (PLCA) wurde in drei Beispielen mit unterschiedlichen Schwerpunkten angewendet. Das erste Anwendungsbeispiel zeigt, dass PLCA für die ökologische Optimierung der Materialauswahl mit Hilfe computergestützter Optimierer geeignet ist. Innerhalb von 15 Minuten konnte das Optimum aus einem Lösungsraum von mehr als 300 Millionen möglichen Lösungen gefunden werden. Das zweite Anwendungsbeispiel zeigt die Möglichkeiten, die PLCA für die ökologische Optimierung der Geometrie in frühen Entwurfsphasen bietet. Mit Hilfe eines halbautomatischen Vorgehens, das Annahmen für die Wahl von Baumaterialien und Gebäudetechnik trifft, konnte die Ökobilanz von geometrischen Varianten berechnet werden, bevor alle nötigen Detailinformationen vorlagen. Im dritten Beispiel wendeten neun Studierende PLCA an, um durch manuelle Variantengenerierung sowohl die Geometrie als auch die Materialauswahl zu optimieren. Im Vergleich zu einer studentischen Referenzgruppe konnten mehr als 40% der potentiellen Umweltwirkungen eingespart werden. Die Bewertung mit Hilfe des Anforderungskatalogs aus Kapitel 2 zeigte, dass alle verpflichtenden Anforderungen erfüllt wurden. Darüber hinaus konnten die negativen Umweltwirkungen der Gebäudeentwürfe in allen Beispielen deutlich reduziert werden. Im Vergleich zu herkömmlichen Ansätzen war PLCA um ein Vielfaches schneller. Gebäudeentwürfe können somit in den entscheidenden frühen Entwurfsphasen zeiteffizient ökologisch optimiert werden. Diese ganzheitliche Optimierung über den gesamten Lebenszyklus war bisher nicht möglich.

Ausblick

Durch die Flexibilität bietet PLCA einen guten Ausgangspunkt für weitere Forschung. In Zukunft können Kennwerte zur Unsicherheit einzelner Parameter in die Methode integriert werden. Damit lassen sich zum einen Ergebnisse nicht nur als einzelne Werte, sondern als Bereiche darstellen. Zum anderen bietet dies die Möglichkeit besonders robuste Lösungen zu identifizieren, die in unterschiedlichen Szenarien gute Ergebnisse erzielen. Darüber hinaus könnte PLCA um ökonomische und soziale Aspekte der Nachhaltigkeit erweitert werden. Da die Weltbevölkerung weiter wächst und Ressourcen knapper werden, gewinnt Nachhaltigkeit in Zukunft weiter an Bedeutung. Architekten und Planer haben die Möglichkeit einen großen Beitrag zur Förderung der Nachhaltigkeit im Gebäudesektor zu leisten. Die Anwendung von Methoden wie PLCA ist dabei ein wichtiger Schritt in Richtung umweltfreundlichere Gebäude.

Appendix

A. Category indicators according to EN 15978

Many different environmental indicators can be found in the literature. The output-related indicators according to EN 15978:2012 which are employed in this thesis are described in the following:

Climate change

Greenhouse gases are gases which accumulate in the troposphere, about 10 km above the earth, and reflect the infrared radiation of the earth. The reflection causes the earth's surface to heat up and provides a moderate temperature (Klöpffer & Grahl 2014, p.235). There are a number of anthropogenic greenhouse gases which have been emitted into the atmosphere and cause an imbalance between incoming energy into the atmosphere (from the sun) and outgoing energy into space. The imbalance causes a rise of the average global temperature, which leads to melting of the polar caps, rise of the sea level, and expansion of deserts, amongst others (IPCC 2013, pp.136–137). The time the gases remain in the atmosphere has to be considered, which is why a time horizon is given for the categorization factor. The Intergovernmental Panel on Climate Change (IPCC) uses a baseline scenario of 100 years (IPCC 2007, p.212).

Indicator:	Global Warming Potential 100 years (GWP_{100})
Unit:	kg CO_2-equivalent
Main cause:	Incineration of fossil fuels (CO_2), agriculture (CH_4), industrial processes (CF_4, SF_6, N_2O)
Effects:	Rise of sea level, floods, expansion of deserts, crop failure

Stratospheric Ozone Depletion

The ozone layer is situated in the lower part of the stratosphere, at around 20 to 30 km above the earth's surface (Fahey & Hegglin 2010, p.Q4). The ozone absorbs about 99% of the sun's UV radiation, which is harmful to humans, animals, and plants. Halogenic molecules in the stratosphere destroy the ozone (Molina & Rowland 1974, p.810). This leads to a decline of ozone concentration in general, and to local phenomena called ozone holes. Two main groups of substances are responsible: chlorofluorocarbons (CFCs) and nitric oxides (NO_X) (König et al. 2009, p.46). A number of man-made substances emit these molecules, most commonly halocarbon refrigerants and foam-blowing agents.

Indicator:	Ozone Depletion Potential (ODP)

Unit: kg R11-equivalent

Main cause: CFCs, HCFCs, NO_X

Effects: Skin cancer (humans and animals), crop failure

Acidification of soil and water

Acidification relates to an increased concentration of hydrogen ions (H+) in the air, water, and soil (JRC European commission 2010b, p.56). Anthropogenically-derived air pollutants like sulphur and nitrogen compounds react to acids, which fall to the ground as 'acid rain'. The pH level of soil and waters falls and causes a decline in the health of forests and kills fish. Other effects include the acidification of the oceans, which is also caused by natural absorption of CO_2 and leads to a decline in coral growth, for example. In addition, acid rain harms historical buildings made of natural stone.

Indicator: Acidification Potential (AP)

Unit: kg SO_2-equivalent

Main cause: Sulphur and nitrogen compounds from the burning of fossil fuels, volcanic ash, CO_2

Effects: Fish and tree mortality, decline of coral reels

Eutrophication

Eutrophication describes the oversupply of nutrients in rivers, lakes, oceans, or soil (Klöpffer & Grahl 2014, p.261). The main cause is the addition of phosphate from detergents, fertilizers, or sewage, and nitrogen compounds from burning fossil fuels. The effects of aquatic eutrophication are, for example, algae growth and increased fish mortality. Terrestrial eutrophication decreases plants' resistance to diseases. Plants adapted to a low nutrient content are endangered because they are overgrown by more competitive species that can take advantage of higher nitrogen levels.

Indicator: Eutrophication Potential (EP)

Unit: kg PO_4^3-equivalent

Main cause: Detergents, fertilizers, sewage, fossil fuels

Effects: Algae growth, fish and plant mortality

Formation of Photo Oxidants

Photo-oxidant formation is the formation of reactive chemical compounds by the action of sunlight (Guinée et al. 2001, p.65). It is also known as photochemical smog or summer smog. Aggressive pollutants, such as nitrogen oxides (NOx) and volatile organic compounds (VOCs), react under the influence of sunlight and create ozone. While ozone is beneficial in the stratosphere, it has a toxic influence on humans at ground level. In addition to ozone, other toxic substances are produced, forming the group of photooxidants. Summer smog greatly depends on regional and meteorological factors (Klöpffer & Grahl 2014, p.252).

Indicator: Photochemical Ozone Creation Potential (POCP)

Unit: kg C_2H_4-equivalent

Main cause: Nitrogen oxides, traffic, burning of fossil fuels

Effects: Toxic for humans, breathing difficulties

Abiotic resource depletion

Udo de Haes (1996, p.19) lists abiotic resource depletion in input-related impact categories. In contrast, EN 15804:2012 and EN 15978:2012 list it as an output-related parameter. These standards employ two indicators for abiotic resource depletion: Abiotic resource depletion potential elements (ADPe) and abiotic resource depletion potential fossil (ADPf).

According to Oers et al. “abiotic resource depletion is the decrease of availability of functions, both in the environment and the economy” (Oers et al. 2002, p.29). These two indicators describe the loss of natural element availability and fossil fuel availability. The indicator ADPe is defined by relating each element to the world’s available reserves which can be exploited economically currently and possibly in future. The annual extraction is divided by the reserves squared. The result is related to the reference element antimony (Sb) through dividing it by the same ratio of availability and current annual extraction. By including the annual extraction rate the current importance of a given resource is captured (JRC European commission 2011, p.100). ADPf is calculated analogously, but instead of the mass of material the lower heating value of the fossil fuel is used. Therefore, the unit is MJ.

Indicator: Abiotic resource depletion potential element (ADPe) /
Abiotic resource depletion potential fossil (ADPf)

Unit: kg Sb-equivalent / MJ

B. Normalization and weighting in DGNB

The calculation process for the environmental criteria related to LCA of DGNB[94] is shown here using the example of the 2015 version for new residential buildings with more than six apartments. The DGNB systems consists of 37 individual criteria. For each criterion, evaluation points (*Bewertungspunkte*, BP) are awarded. These are weighted and added together to provide the overall score a building achieves. DGNB employs two criteria related to LCA: ENV1.1 for output-related impacts and ENV2.1 for the primary energy demand. They make up 7.9% and 5.6% respectively of all BP that can be achieved. This indicates that, with 13.5% of the total, the LCA-related criteria have a great importance for the DGNB system. With exception of ADPe and ADPf, DGNB employs all output-related indicators defined in EN 15978:2012. To compensate for neglecting certain small building components due to the simplification, DGNB adds 10% to the results at the end. The functional unit in DGNB is always 1 m² of net floor area (NFA) and 1 year of operation. The calculation of BP is based on the so-called *check list points* (CLP) for each criterion. To calculate the CLP for both criteria (ENV1.1 and ENV2.1.) four steps are necessary: Normalization of the LCA results, calculation of sub-points called *Teilpunkte* (TP), weighting of TP, and the aggregation into CLP.

Normalization

The reference values for normalization (R) are provided separately for the operational impact (R_{Nref}) and the embodied impact (R_{Kref}). Reference values for embodied impact are shown in Table 53 and Table 54.

Table 53: Reference values for embodied impact (R_{Kref}) according to DGNB ENV1.1 residential buildings 2015

GWP_{Kref} [kg $CO_2e/m^2_{NFA}\times a$]	ODP_{Kref} [kg R11e/$m^2_{NFA}\times a$]	$POCP_{Kref}$ [kg $C_2H_4e/m^2_{NFA}\times a$]	AP_{Kref} [kg $SO_2e/m^2_{NFA}\times a$]	EP_{Kref} [kg $PO_4^{3-}e/m^2_{NFA}\times a$]
9.4	5.3E-07	0.0042	0.037	0.0047

Table 54: Reference values for embodied impact (R_{Kref}) according to DGNB ENV2.1 residential buildings 2015

$PENRT_{Kref}$ [MJ / $m^2_{NFA}\times a$]	PET_{Kref} [MJ / $m^2_{NFA}\times a$]	$PERT/PENRT_{Kref}$ [%]
123	151	-

[94] The DGNB criteria catalogue can be requested at http://www.dgnb-system.de/en/services/request-dgnb-criteria/ (accessed March 21st 2016)

The reference values for operational impact depend on the results for the energy demand of the reference building according to EnEV 2014. The reference values are provided separately for electricity demand and heating demand and then summed up. The reference values are shown in Table 55 and Table 56. *Sref* refers to the electricity demand and *Wref* to the heating demand. Both refer to the final energy demand and are declared in $kWh/m^2_{NFA} \times a$.

Table 55: Reference values for operational impact (R_{Nref}) according to DGNB ENV1.1 residential buildings 2015

	GWP_{Nref} [kg $CO_2e/m^2_{NFA} \times a$]	ODP_{Nref} [kg $R11e/m^2_{NFA} \times a$]	$POCP_{Nref}$ [kg $C_2H_4e/m^2_{NFA} \times a$]	AP_{Nref} [kg $SO_2e/m^2_{NFA} \times a$]	EP_{Nref} [kg $PO_4^{3-}e/m^2_{NFA} \times a$]
Sref	0.62	3.07E-09	7.60E-05	1.03E-03	9.92E-05
Wref	0.25	1.80E-11	3.10E-05	2.70E-04	1.90E-05

Table 56: Reference values for operational impact (R_{Nref}) according to DGNB ENV2.1 residential buildings 2015

	$PENRT_{Nref}$ [MJ / $m^2_{NFA} \times a$]	PET_{Nref} [MJ / $m^2_{NFA} \times a$]	$PERT/PET_{Nref}$ [%]
Sref	8.80	10.30	-
Wref	3.8	3.90	-

Calculation of TP

The TP range between 0 and 100 points. They are awarded for undercutting the reference value (R) multiplied by a factor provided in Table 57 to Table 59. For example, if the GWP of a building design is lower than 0.88 × GWP_{ref}, this design achieves 70 TP for the indicator GWP.

Table 57: Factors for the calculation of TP according to DGNB ENV1.1 residential buildings 2015

TP	GWP	ODP	POCP	AP	EP
10	1.40	10.0	2.00	1.700	2.00
20	1.30	7.75	1.75	1.525	1.75
30	1.20	5.50	1.50	1.350	1.50
40	1.10	3.25	1.25	1.175	1.25
50	1.00	1.00	1.00	1.00	1.00
60	0.94	0.94	0.94	0.94	0.94
70	0.88	0.88	0.88	0.88	0.88
80	0.82	0.82	0.82	0.82	0.82
90	0.76	0.76	0.76	0.76	0.76
100	0.70	0.70	0.70	0.70	0.70

Table 58: Factors for the calculation of TP for PENRT according to DGNB ENV2.1 residential buildings 2015

TP	PENRT
10	1.40
20	1.30
30	1.20
40	1.10
50	1.00
60	0.94
70	0.88
80	0.82
90	0.76
100	0.70

Table 59: Factors for the calculation of TP for PERT/PET according to DGNB ENV2.1 residential buildings 2015

TP	PERT/PET
5	2%
10	4%
15	6%
20	8%
25	10%
30	12%
35	14%
40	16%
45	18%
50	20%

Table 60: Factors for the calculation of TP for PET according to DGNB ENV2.1 residential buildings 2015

TP	PET
5	1.40
10	1.30
15	1.20
20	1.10
25	1.00
30	0.94
35	0.88
40	0.82
45	0.76
50	0.70
55	0.67
60	0.64
65	0.61
70	0.58
75	0.55
80	0.52
85	0.49
90	0.46
95	0.43
100	0.40

Weighting

The TP are weighted by the weighting factors (G) provided in Table 61 and Table 62.

Table 61: Weighting factors according to DGNB ENV1.1 residential buildings 2015

G_{GWP}	G_{ODP}	G_{POCP}	G_{AP}	G_{EP}
40%	15%	15%	15%	15%

Table 62: Weighting factors according to DGNB ENV2.1 residential buildings 2015

G_{PENRT}	G_{PET}	$G_{PERT/PET}$
60%	40%	20%

Calculation of CLP

In the last step the CLP for ENV1.1 and ENV2.1 are calculated by summing up the TP multiplied by the weighting factors (G), see Equations B1 and B2.

$$CLP = TP_{GWP} \times G_{GWP} + TP_{ODP} \times G_{ODP} + TP_{POCP} \times G_{POCP} + TP_{AP} \times G_{AP} + TP_{EP} \times G_{EP} \quad \text{(B1)}$$

$$CLP = TP_{PENRT} \times G_{PENRT} + TP_{PET} \times G_{PET} + TP_{PERT/PET} \times G_{PERT/PET} \quad \text{(B2)}$$

A maximum of 100 CLP can be achieved for both criteria ENV1.1 and ENV2.1.

Calculation of BP

For both criteria ENV1.1 and ENV2.1 BP equals CLP divided by 10. As such a maximum of 10 BP can be achieved for both criteria.

C. Environmental data of modified components for Concretecube

Table 63 to Table 65 show the environmental data of the modified building components for Concretecube.

Table 63: Environmental data for concrete exterior wall

	#	Name	Amount		GWP [kg CO²e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [M]	PERT [MJ]
Production	1	Plaster	32.00	kg	11.9723	3.22E-07	0.0034148	0.0243	0.0046385	123.41	9.24
	2	EPS	0.18	m³	15.6505	4.70E-07	5.55E-03	0.034	3.68E-03	479.27	2.13
	3	Concrete	0.18	m³	4.88	9.46E-07	6.42E-03	0.0631	8.96E-03	182.14	3.31
	4	Reinforcement	28.26	kg	24.7093	2.22E-06	7.74E-03	0.0464	3.92E-03	351.05	27.85
	5	Gypsum Plaster	24.00	kg	3.8609	1.87E-07	0.0004509	0.0048268	0.0005321	54.18	1.16
	Sum per m²				61.0698	4.143E-06	0.0235815	0.1726268	0.0217313	1190.0491	43.6857
Replacement	1	Plaster	1		12.6141	3.27E-07	0.0038345	0.0269	0.0049883	128.54	9.58
	2	EPS	1		23.6654	-1.53E-09	4.60E-03	0.0238	2.81E-03	308.38	-0.11
	3	Concrete	0								
	4	Reinforcement	0								
	5	Gypsum Plaster	0								
	Sum per m²				36.2795	3.257E-07	0.0084328	0.0507	0.0077969	436.9184	9.4692
EOL	1	Plaster	32.00	kg	0.6418	5.29E-09	0.0004197	0.0026414	0.0003498	5.13	0.34
	2	EPS	0.18	m³	8.0149	-4.72E-07	-0.000952	-0.0102	-0.000875	-170.89	-2.24
	3	Concrete	0.18	m³	14.5696	-1.57E-07	2.12E-03	0.0284	4.16E-03	19.82	-0.68
	4	Reinforcement	28.26	kg	0.9869	-1.06E-08	1.43E-04	1.92E-03	2.82E-04	1.34	-0.05
	5	Gypsum Plaster	24.00	kg	0.8382	-9.04E-09	1.22E-04	1.63E-03	2.39E-04	1.14	-0.04
	Sum per m²				25.0514	-6.43E-07	0.001848	0.0243997	0.0041512	-143.4586	-2.6611
LC	Sum per m²				122.4007	3.826E-06	0.0338623	0.2477265	0.0336795	1483.5089	50.4938

Table 64: Environmental data for concrete ceiling with parquet floor

	#	Name	Amount		GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg $PO_4{}^3e$]	PENRT [M]	PERT [MJ]
Production	1	Wooden flooring	1.00	m²	-40.810	1.00E-06	0.0038	0.0219	0.0033	216.72	502.49
	2	Dry screed	2.60	kg	-0.250	8.40E-08	0.0012	0.0113	0.0015	83.29	67.62
	3	Separating foil	0.80	kg	-0.510	8.98E-08	0.0003	0.0034	0.0009	11.53	24.53
	4	Dry screed	2.60	kg	-0.250	8.40E-08	0.0012	0.0113	0.0015	83.29	67.62
	5	Impact sound insulation	3.90	kg	-0.380	1.26E-07	0.0018	0.0169	0.0023	124.93	101.43
	6	Filling	60.00	kg	28.460	3.19E-07	0.0049	0.0454	0.0053	397.48	1.70
	7	Separating foil	0.80	kg	-0.510	8.98E-08	0.0003	0.0034	0.0009	11.53	24.53
	8	Concrete	0.19	m³	36.810	9.99E-07	0.0068	0.0666	0.0095	192.26	3.50
	9	Reinforcement	29.83	kg	26.080	2.34E-06	0.0082	0.0490	0.0041	370.55	29.39
	10	Wooden cladding	0.02	m³	-20.410	8.36E-07	0.0021	0.0214	0.0025	145.20	279.53
	Sum per m²				**28.230**	**5.968E-06**	**0.0306**	**0.2506**	**0.0318**	**1636.78**	**1102.34**
Replacement	1	Wooden flooring	0								
	2	Dry screed	0								
	3	Separating foil	0								
	4	Dry screed	0								
	5	Impact sound insulation	0								
	6	Filling	0								
	7	Separating foil	0								
	8	Concrete	0								
	9	Reinforcement	0								
	10	Wooden cladding	0								
	Sum per m²				**0**	**0**	**0**	**0**	**0**	**0**	**0**
EOL	1	Wooden flooring	11.50	kg	13.530	-2.59E-07	0.0000	0.0095	0.0025	-117.93	-1.23
	2	Dry screed	2.60	kg	1.080	-1.37E-07	-0.0003	-0.0020	-0.0003	-58.58	-0.65
	3	Separating foil	0.80	kg	0.650	-5.97E-08	-0.0001	-0.0011	-0.0001	-22.08	-0.29
	4	Dry screed	2.60	kg	1.080	-1.37E-07	-0.0003	-0.0020	-0.0003	-58.58	-0.65
	5	Impact sound insulation	3.90	kg	1.610	-2.05E-07	-0.0004	-0.0030	-0.0004	-87.87	-0.97
	6	Filling	60.00	kg	1.200	9.92E-09	0.0008	0.0050	0.0007	9.61	0.64
	7	Separating foil	0.80	kg	0.650	-5.97E-08	-0.0001	-0.0011	-0.0001	-22.08	-0.29
	8	Concrete	440.4	kg	14.410	-2.82E-07	0.0020	0.0278	0.0041	6.15	-1.27
	9	Reinforcement									
	10	Wooden cladding	13.22	kg	13.150	-4.31E-07	-0.0008	-0.0054	0.0000	-180.97	-2.05
	Sum per m²				**47.360**	**-1.56E-06**	**0.0008**	**0.0277**	**0.0061**	**-532.33**	**-6.76**
LC	**Sum per m²**				**75.590**	**4.407E-06**	**0.0314**	**0.2783**	**0.0379**	**1104.45**	**1095.58**

Table 65: Environmental data for concrete ceiling bathroom

	#	Name	Amount		GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [M]	PERT [MJ]
Production	1	Tiles	10.00	kg	2.830	1.10E-07	0.0003	0.00555	0.0005	47.54	0.52
	2	Tile adhesive	3.75	kg	1.030	2.75E-08	0.0003	0.00195	0.0003	7.17	0.64
	3	Dry screed	2.60	kg	-0.250	8.40E-08	0.0012	0.01127	0.0015	83.29	67.62
	4	Separating foil	0.80	kg	-0.510	8.98E-08	0.0003	0.00338	0.0009	11.53	24.53
	5	Dry screed	2.60	kg	-0.250	8.40E-08	0.0012	0.01127	0.0015	83.29	67.62
	6	Impact sound insulation	3.90	kg	-0.380	1.26E-07	0.0018	0.01691	0.0023	124.93	101.43
	7	Filling	60.00	kg	28.460	3.19E-07	0.0049	0.04539	0.0053	397.48	1.70
	8	Separating foil	0.80	kg	-0.510	8.98E-08	0.0003	0.00338	0.0009	11.53	24.53
	9	Concrete	0.19	m³	36.810	9.99E-07	0.0068	0.06662	0.0095	192.26	3.50
	10	Reinforcement	29.83	kg	26.080	2.34E-06	0.0082	0.04899	0.0041	370.55	29.39
	11	Wooden cladding	0.02	m³	-20.410	8.36E-07	0.0021	0.02141	0.0025	145.20	279.53
	Sum per m²				**61.0698**	**4.143E-06**	**0.0235815**	**72.900**	**5.105E-06**	**0.0274**	**0.23612**
Replacement	1	Tiles	0								
	2	Tile adhesive	0								
	3	Dry screed	0								
	4	Separating foil	0								
	5	Dry screed	0								
	6	Impact sound insulation	0								
	7	Filling	0								
	8	Separating foil	0								
	9	Concrete	0								
	10	Reinforcement	0								
	11	Wooden cladding	0								
	Sum per m²				**0**	**0**	**0**	**0**	**0**	**0**	**0**
EOL	1	Tiles	10.00	kg	0.200	1.65E-09	0.00010	0.00080	0.0001	1.60	0.11
	2	Tile adhesive	3.75	kg	0.080	6.20E-10	0.00000	0.00030	0.0000	0.60	0.04
	3	Dry screed	2.60	kg	1.080	-1.37E-07	-0.00030	-0.00200	-0.0003	-58.58	-0.65
	4	Separating foil	0.80	kg	0.650	-5.97E-08	-0.00010	-0.00110	-0.0001	-22.08	-0.29
	5	Dry screed	2.60	kg	1.080	-1.37E-07	-0.00030	-0.00200	-0.0003	-58.58	-0.65
	6	Impact sound insulation	3.90	kg	1.610	-2.05E-07	-0.00040	-0.00300	-0.0004	-87.87	-0.97
	7	Filling	60.00	kg	1.200	9.92E-09	0.00080	0.00500	0.0007	9.61	0.64
	8	Separating foil	0.80	kg	0.650	-5.97E-08	-0.00010	-0.00110	-0.0001	-22.08	-0.29
	9	Concrete	440.4	kg	14.410	-2.82E-07	0.00200	0.02780	0.0041	6.15	-1.27
	10	Reinforcement									
	11	Wooden cladding	13.22	kg	13.150	-4.31E-07	-0.00080	-0.00540	0.0000	-180.97	-2.05
	Sum per m²				**34.110**	**-1.3E-06**	**0.00090**	**0.01930**	**0.0037**	**-412.2**	**-5.38**
LC	Sum per m²				**107.010**	**3.806E-06**	**0.02830**	**0.25542**	**0.0330**	**1062.57**	**595.63**

D. Detailed results for verification of embodied impact

Here, the result for the embodied impact are shown. First of all, the results of the original study are provided in Table 67. Some components, e.g. the elevator, have not been modelled with CAALA. Therefore, the results for the study with reduced building components are shown in Table 68. These values serve as references for the following comparisons.

For both reference buildings, Woodcube and Concretecube, the analysis consists of two steps. In the first step, the results from the original study by Hartwig are compared to those of the modified areas in order to investigate the influence of differences in area in the geometric model on the results. In the second step, the results of the modified areas are compared to those provided study by CAALA, in order to find out if the algorithms calculate correctly. The results are provided in different tables. An overview of the individual tables is provided in Table 66.

Table 66: Overview on tables with results for verification

	Results	Table
Woodcube	Original study	Table 67
	Reduced study (Hartwig)	Table 68
	Method results (CAALA)	Table 69
	Difference between CAALA – Hartwig	Table 70
	Deviation between CAALA – Hartwig	Table 71
	Method results with modified areas (CAALA modified)	Table 72
	Difference between CAALA modified – Hartwig	Table 73
	Deviation between CAALA modified – Hartwig	Table 74
Concretecube	Original areas	Table 75
	Modified areas	Table 76
	Difference between modified areas – reduced study	Table 77
	Deviation between modified areas – reduced study	Table 78
	Results of CAALA	Table 79
	Difference between CAALA - modified areas	Table 80
	Deviation between CAALA - modified areas	Table 81

Table 67: Results for embodied impact, original study by Hartwig (2012)

Name	Area [m²/ pieces]	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	741.95	-82808	2.39E-03	12.500	99.990	21.980	-475189	3074486
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123979	6763
Exterior wall staircase above roof	20.04	2846	6.44E-05	1.030	9.420	1.260	30905	36505
Interior wall staircase	208.15	22358	8.85E-04	4.910	41.470	5.130	164552	9146
Interior wall staircase basement	52.78	6050	2.00E-04	1.680	14.830	1.880	53201	33424
Interior wall elevator	135.61	15174	6.00E-04	3.330	28.140	3.480	111675	6207
Interior wall	498.29	7177	3.57E-04	1.430	13.510	2.290	119248	46265
Interior partition wall	93.84	2492	1.24E-04	0.630	5.470	0.980	42063	20333
Interior wall basement	52.46	1708	2.87E-05	0.290	2.320	0.310	13927	669
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	24.00	4698	1.10E-04	1.000	7.290	0.900	46503	1177
Wooden roof	204.00	-5549	4.59E-04	4.070	24.340	4.840	32389	543547
Wooden ceiling with parquet floor	612.67	-45386	1.99E-03	14.080	115.160	21.850	61081	2161445
Wooden ceiling bathroom	55.61	-2197	1.44E-04	1.090	9.060	1.680	2982	165605
Basement ceiling with parquet floor	121.62	3438	1.03E-03	5.770	55.520	7.850	123839	443555
Concrete ceiling staircase	36.36	3092	1.22E-04	0.680	5.730	0.710	22756	1265
Basement ceiling entrance interior	19.90	562.56	1.68E-04	0.940	9.090	1.280	20263	72576
Basement ceiling entrance exterior	22.67	2024	7.85E-05	0.440	3.710	0.460	14590	796
Basement ceiling bathroom	13.82	1751	5.81E-05	0.450	4.010	0.520	17785	9055
Wooden balcony	99.69	-22137	6.33E-04	7.290	17.570	4.490	-146468	730650
Small window	13 pc.	752	4.21E-05	0.530	3.600	0.500	9180	3495
Medium window	12 pc.	1136	5.44E-05	0.710	5.380	0.750	13525	4362
Large window	28 pc.	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	1 pc.	859	2.42E-05	0.330	3.820	0.560	9905	1006
Apartment door	9 pc.	-177	1.22E-05	0.040	0.360	0.070	-593	8419
Balcony door	13 pc.	10410	3.00E-04	4.110	46.380	6.820	120028	12840
Basement interior door	4 pc.	303	1.22E-05	0.100	0.670	0.060	4022	231
Interior door	31 pc.	-608	4.19E-05	0.130	1.240	0.220	-2043	29000
Terrace	0´ pc.	0	0.00E+00	0.000	0.000	0.000	0	0
Pile foundation	40 pc.	24026	9.32E-04	5.200	44.080	5.470	173155	9445
District heating connection	40 kW	432	4.33E-05	0.090	0.970	0.300	6298	368
Elevator	1 pc.	13388	1.05E-03	4.110	52.650	18.490	172783	17200
Sum		**25764**	**1.43E-02**	**91.665**	**750.509**	**131.051**	**1217880**	**7479612**

Table 68: Results for embodied impact, Woodcube, reduced study

Name	Area [m^2]	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	741.95	-82808	2.39E-03	12.500	99.990	21.980	-475189	3074486
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123979	6763
Exterior wall staircase above roof	20.04	2846	6.44E-05	1.030	9.420	1.260	30905	36505
Interior wall staircase	208.15	22358	8.85E-04	4.910	41.470	5.130	164552	9146
Interior wall staircase basement	52.78	6050	2.00E-04	1.680	14.830	1.880	53201	33424
Interior wall elevator	135.61	15174	6.00E-04	3.330	28.140	3.480	111675	6207
Interior wall	498.29	7177	3.57E-04	1.430	13.510	2.290	119248	46265
Interior partition wall	93.84	2492	1.24E-04	0.630	5.470	0.980	42063	20333
Interior wall basement	52.46	1708	2.87E-05	0.290	2.320	0.310	13927	669
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	24.00	4698	1.10E-04	1.000	7.290	0.900	46503	1177
Wooden roof	204.00	-5549	4.59E-04	4.070	24.340	4.840	32389	543547
Wooden ceiling with parquet floor	612.67	-45386	1.99E-03	14.080	115.160	21.850	61081	2161445
Wooden ceiling bathroom	55.61	-2197	1.44E-04	1.090	9.060	1.680	2982	165605
Basement ceiling with parquet floor	121.62	3438	1.03E-03	5.770	55.520	7.850	123839	443555
Concrete ceiling staircase	36.36	3092	1.22E-04	0.680	5.730	0.710	22756	1265
Basement ceiling entrance interior	19.90	563	1.68E-04	0.940	9.090	1.280	20263	72576
Basement ceiling entrance exterior	22.67	2024	7.85E-05	0.440	3.710	0.460	14590	796
Basement ceiling bathroom	13.82	1751	5.81E-05	0.450	4.010	0.520	17785	9055
Wooden balcony	99.69	-22137	6.33E-04	7.290	17.570	4.490	-146468	730650
Small window	6.37	752	4.21E-05	0.530	3.600	0.500	9180	3495
Medium window	10.83	1136	5.44E-05	0.710	5.380	0.750	13525	4362
Large window	54.88	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	9.89	859	2.42E-05	0.330	3.820	0.560	9905	1006
Apartment door	18.00	-177	1.22E-05	0.040	0.360	0.070	-593	8419
Balcony door	119.60	10410	3.00E-04	4.110	46.380	6.820	120028	12840
Basement interior door	8.00	303	1.22E-05	0.100	0.670	0.060	4022	231
Interior door	55.80	-608	4.19E-05	0.130	1.240	0.220	-2043	29000
Sum	**3707.85**	**-12082**	**1.23E-02**	**82.265**	**652.809**	**106.791**	**865644**	**7452599**

Table 69: Results for embodied impact, Woodcube, CAALA

Name	Area [m²]	GWP [kg CO²e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	713.58	-79642	2.30E-03	12.022	96.167	21.140	-457019	2956900
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123980	6763
Exterior wall staircase above roof	14.05	1996	4.50E-05	0.722	6.606	0.884	21671	25598
Interior wall staircase	259.87	27914	1.11E-03	6.130	51.775	6.405	205442	11419
Interior wall staircase basement	52.73	6045	2.00E-04	1.679	14.817	1.878	53154	33395
Interior wall elevator	137.56	15392	6.09E-04	3.378	28.545	3.530	113284	6296
Interior wall	549.62	7916	3.94E-04	1.577	14.902	2.526	131531	51031
Interior partition wall	100.71	2675	1.33E-04	0.676	5.871	1.052	45144	21822
Interior wall basement	62.91	2049	3.40E-05	0.348	2.782	0.372	16702	802
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	25.14	4921	1.15E-04	1.048	7.637	0.943	48714	1233
Wooden roof	202.87	-5518	4.56E-04	4.047	24.205	4.813	32209	540534
Wooden ceiling with parquet floor	736.35	-56115	2.46E-03	17.409	142.382	27.015	75521	2672418
Wooden ceiling bathroom	63.71	-2517	1.65E-04	1.249	10.379	1.925	3416	189718
Basement ceiling with parquet floor	156.21	4416	1.32E-03	7.411	71.309	10.082	159056	569692
Concrete ceiling staircase	36.16	3075	1.21E-04	0.676	5.698	0.706	22630	1258
Basement ceiling entrance interior	11.21	317	9.50E-05	0.529	5.120	0.721	11413	40878
Basement ceiling entrance exterior	21.15	1889	7.30E-05	0.411	3.461	0.429	13612	743
Basement ceiling bathroom	16.74	2121	7.00E-05	0.545	4.857	0.630	21540	10967
Wooden balcony	90.68	-20136	5.76E-04	6.631	15.982	4.084	-133228	664603
Small window	6.37	752	4.20E-05	0.530	3.600	0.500	9180	3495
Medium window	10.83	1136	5.40E-05	0.710	5.380	0.750	13525	4362
Large window	54.88	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	9.89	859	2.40E-05	0.332	3.819	0.561	9905	1006
Apartment door	18.21	-179	1.20E-05	0.040	0.364	0.071	-600	8518
Balcony door	128.57	11190	3.23E-04	4.418	49.859	7.332	129030	13803
Basement interior door	8.09	306	1.20E-05	0.101	0.678	0.061	4069	234
Interior door	55.80	-608	4.20E-05	0.130	1.240	0.220	-2043	29000
Sum	**3954.93**	**-9797**	**1.31E-02**	**87.455**	**702.163**	**114.549**	**1003378**	**7896264**

Table 70: Differences of embodied impact, Woodcube, Hartwig - CAALA

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	-3166	9.10E-05	0.478	3.823	0.840	-18170	117600
Exterior wall basement	0	0.00E+00	0.000	0.000	0.000	-1	0
Exterior wall staircase above roof	850	1.90E-05	0.308	2.814	0.376	9234	10907
Interior wall staircase	-5556	-2.20E-04	-1.220	-10.305	-1.275	-40890	-2273
Interior wall staircase basement	5	0.00E+00	0.001	0.013	0.002	47	29
Interior wall elevator	-219	-9.00E-06	-0.048	-0.405	-0.050	-1609	-89
Interior wall	-739	-3.70E-05	-0.147	-1.392	-0.236	-12283	-4766
Interior partition wall	-183	-9.00E-06	-0.046	-0.401	-0.072	-3081	-1489
Interior wall basement	-340	-5.00E-06	-0.058	-0.462	-0.062	-2775	-133
Bottom slab	0	0.00E+00	0.000	0.000	0.000	0	0
Roof above staircase	-223	-5.00E-06	-0.048	-0.347	-0.043	-2211	-56
Wooden roof	-31	3.00E-06	0.023	0.135	0.027	180	3013
Wooden ceiling with parquet floor	10729	-4.71E-04	-3.329	-27.224	-5.165	-14440	-511000
Wooden ceiling bathroom	320	-2.10E-05	-0.159	-1.319	-0.245	-434	-24113
Basement ceiling with parquet floor	-978	-2.93E-04	-1.641	-15.789	-2.232	-35217	-126137
Concrete ceiling staircase	17	1.00E-06	0.004	0.032	0.004	126	7
Basement ceiling entrance interior	246	7.30E-05	0.411	3.970	0.559	8850	31698
Basement ceiling entrance exterior	136	5.00E-06	0.029	0.249	0.031	978	53
Basement ceiling bathroom	-370	-1.20E-05	-0.095	-0.847	-0.110	-3755	-1912
Wooden balcony	-2001	5.70E-05	0.659	1.588	0.406	-13240	66047
Small window	0	0.00E+00	0.000	0.000	0.000	0	0
Medium window	0	0.00E+00	0.000	0.000	0.000	0	0
Large window	0	0.00E+00	0.000	0.000	0.000	0	0
Entrance door	0	0.00E+00	0.000	0.000	0.000	0	0
Apartment door	2	0.00E+00	0.000	-0.004	-0.001	7	-99
Balcony door	-781	-2.30E-05	-0.308	-3.479	-0.512	-9002	-963
Basement interior door	-4	0.00E+00	-0.001	-0.008	-0.001	-47	-3
Interior door	0	0.00E+00	0.000	0.000	0.000	0	0
Sum	**-2285**	**-8.56E-04**	**-5.19**	**-49.36**	**-7.76**	**-137734**	**-443678**

Table 71: Deviation of embodied impact, Woodcube, Hartwig - CAALA

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	3.824	3.808	3.824	3.824	3.824	3.824	3.825
Exterior wall basement	-0.001	0.000	-0.001	-0.001	-0.001	-0.001	-0.001
Exterior wall staircase above roof	29.877	29.688	29.877	29.877	29.877	29.877	29.877
Interior wall staircase	-24.849	-24.859	-24.849	-24.849	-24.849	-24.849	-24.849
Interior wall staircase basement	0.088	0.000	0.088	0.088	0.088	0.088	0.088
Interior wall elevator	-1.441	-1.500	-1.441	-1.441	-1.441	-1.441	-1.441
Interior wall	-10.301	-10.364	-10.301	-10.301	-10.301	-10.301	-10.301
Interior partition wall	-7.324	-7.258	-7.324	-7.324	-7.324	-7.324	-7.324
Interior wall basement	-19.927	-17.241	-19.927	-19.927	-19.927	-19.927	-19.927
Bottom slab	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Roof above staircase	-4.754	-4.545	-4.754	-4.754	-4.754	-4.754	-4.754
Wooden roof	0.554	0.654	0.554	0.554	0.554	0.554	0.554
Wooden ceiling with parquet floor	-23.640	-23.668	-23.640	-23.640	-23.641	-23.640	-23.642
Wooden ceiling bathroom	-14.560	-14.583	-14.560	-14.560	-14.560	-14.560	-14.560
Basement ceiling with parquet floor	-28.438	-28.447	-28.438	-28.438	-28.438	-28.438	-28.438
Concrete ceiling staircase	0.555	0.820	0.555	0.555	0.555	0.555	0.555
Basement ceiling entrance interior	43.676	43.452	43.676	43.676	43.676	43.676	43.676
Basement ceiling entrance exterior	6.702	6.410	6.702	6.702	6.702	6.702	6.702
Basement ceiling bathroom	-21.114	-20.690	-21.114	-21.114	-21.114	-21.114	-21.114
Wooden balcony	9.039	9.005	9.039	9.039	9.039	9.039	9.039
Small window	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Medium window	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Large window	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Entrance door	0.000	0.000	-0.037	0.001	-0.009	0.000	-0.001
Apartment door	-1.173	0.000	-1.172	-1.173	-1.173	-1.173	-1.173
Balcony door	-7.500	-7.667	-7.500	-7.500	-7.500	-7.500	-7.500
Basement interior door	-1.173	0.000	-1.173	-1.173	-1.173	-1.173	-1.173
Interior door	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sum	**18.909**	**-6.987**	**-6.306**	**-7.561**	**-7.264**	**-15.911**	**-5.953**

Table 72: Results for embodied impact, Woodcube, CAALA modified

Name	Area [m²]	GWP [kg CO²e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	741.95	-82808	2.39E-03	12.500	99.990	21.980	-475189	3074500
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123979	6763
Exterior wall staircase above roof	20.04	2846	6.40E-05	1.030	9.420	1.260	30905	36505
Interior wall staircase	208.15	22358	8.85E-04	4.910	41.470	5.130	164552	9146
Interior wall staircase basement	52.78	6050	2.00E-04	1.680	14.830	1.880	53201	33424
Interior wall elevator	135.61	15174	6.00E-04	3.330	28.140	3.480	111675	6207
Interior wall	498.29	7177	3.57E-04	1.430	13.510	2.290	119248	46265
Interior partition wall	93.84	2492	1.24E-04	0.630	5.470	0.980	42063	20333
Interior wall basement	52.46	1708	2.90E-05	0.290	2.320	0.310	13927	669
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	24.00	4698	1.10E-04	1.000	7.290	0.900	46503	1177
Wooden roof	204.00	-5549	4.59E-04	4.070	24.340	4.840	32389	543547
Wooden ceiling with parquet floor	612.67	-45386	1.99E-03	14.080	115.158	21.850	61081	2161418
Wooden ceiling bathroom	55.61	-2197	1.44E-04	1.090	9.060	1.680	2982	165605
Basement ceiling with parquet floor	121.62	3438	1.03E-03	5.770	55.520	7.850	123839	443555
Concrete ceiling staircase	36.36	3092	1.22E-04	0.680	5.730	0.710	22756	1265
Basement ceiling entrance interior	19.90	563	1.68E-04	0.940	9.090	1.280	20263	72576
Basement ceiling entrance exterior	22.67	2024	7.80E-05	0.440	3.710	0.460	14590	796
Basement ceiling bathroom	13.82	1751	5.80E-05	0.450	4.010	0.520	17785	9055
Wooden balcony	99.69	-22137	6.33E-04	7.290	17.570	4.490	-146468	730650
Small window	6.37	752	4.20E-05	0.530	3.600	0.500	9180	3495
Medium window	10.83	1136	5.40E-05	0.710	5.380	0.750	13525	4362
Large window	54.88	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	9.89	859	2.40E-05	0.332	3.819	0.561	9905	1006
Apartment door	18.00	-177	1.20E-05	0.040	0.360	0.070	-593	8419
Balcony door	119.60	10410	3.00E-04	4.110	46.380	6.820	120028	12840
Basement interior door	8.00	303	1.20E-05	0.100	0.670	0.060	4022	231
Interior door	55.80	-608	4.20E-05	0.130	1.240	0.220	-2043	29000
Sum	**3707.85**	**-12082**	**1.23E-02**	**82.267**	**652.807**	**106.791**	**865644**	**7452586**

Table 73: Differences of embodied impact, Woodcube, Hartwig – CAALA modified

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	0.000	0.00E+00	0.000	0.000	0.000	0.000	-14.000
Exterior wall basement	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Exterior wall staircase above roof	0.000	4.00E-07	0.000	0.000	0.000	0.000	0.000
Interior wall staircase	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall staircase basement	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall elevator	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior partition wall	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall basement	0.000	-3.00E-07	0.000	0.000	0.000	0.000	0.000
Bottom slab	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Roof above staircase	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Wooden roof	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Wooden ceiling with parquet floor	0.128	0.00E+00	0.000	0.002	0.000	-0.161	27.255
Wooden ceiling bathroom	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement ceiling with parquet floor	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Concrete ceiling staircase	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance interior	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance exterior	0.000	5.00E-07	0.000	0.000	0.000	0.000	0.000
Basement ceiling bathroom	0.000	1.00E-07	0.000	0.000	0.000	0.000	0.000
Wooden balcony	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Small window	0.000	1.00E-07	0.000	0.000	0.000	0.000	0.000
Medium window	0.000	4.00E-07	0.000	0.000	0.000	0.000	0.000
Large window	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Entrance door	-0.002	2.00E-07	-0.002	0.001	-0.001	0.108	-0.129
Apartment door	0.000	2.00E-07	0.000	0.000	0.000	0.000	0.000
Balcony door	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement interior door	0.000	2.00E-07	0.000	0.000	0.000	0.000	0.000
Interior door	0.000	-1.00E-07	0.000	0.000	0.000	0.000	0.000
Sum	**0.126**	**1.70E-06**	**-0.002**	**0.002**	**0.000**	**-0.053**	**13.126**

Table 74: Deviation of embodied impact, Woodcube, Hartwig - CAALA modified

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg $PO_4{}^3e$]	PENRT [MJ]	PERT [MJ]
Wooden exterior wall	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Exterior wall basement	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Exterior wall staircase above roof	0.000	0.621	0.000	0.000	0.000	0.000	0.000
Interior wall staircase	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall staircase basement	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall elevator	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior partition wall	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall basement	0.000	-1.045	0.000	0.000	0.000	0.000	0.000
Bottom slab	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Roof above staircase	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Wooden roof	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Wooden ceiling with parquet floor	0.000	0.000	-0.001	0.002	0.002	0.000	0.001
Wooden ceiling bathroom	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement ceiling with parquet floor	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Concrete ceiling staircase	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance interior	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance exterior	0.000	0.637	0.000	0.000	0.000	0.000	0.000
Basement ceiling bathroom	0.000	0.172	0.000	0.000	0.000	0.000	0.000
Wooden balcony	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Small window	0.000	0.238	0.000	0.000	0.000	0.000	0.000
Medium window	0.000	0.735	0.000	0.000	0.000	0.000	0.000
Large window	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Entrance door	0.000	0.826	-0.633	0.016	-0.148	0.001	-0.013
Apartment door	0.000	1.639	0.000	0.000	0.000	0.000	0.000
Balcony door	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement interior door	0.000	1.639	0.000	0.000	0.000	0.000	0.000
Interior door	0.000	-0.239	0.000	0.000	0.000	0.000	0.000
Sum	-0.001	0.014	-0.003	0.000	0.000	0.000	0.000

Table 75: Results for embodied impact, Concretecube, Hartwig

Name	Area [m²]	GWP [kg CO²e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	741.95	90815	2.84E-03	25.124	183.801	24.988	1100689	37464
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123979	6763
Exterior wall staircase above roof	20.04	2846	6.44E-05	1.030	9.420	1.260	30905	36505
Interior wall staircase	208.15	22358	8.85E-04	4.910	41.470	5.130	164552	9146
Interior wall staircase basement	52.78	6050	2.00E-04	1.680	14.830	1.880	53201	33424
Interior wall elevator	135.61	15174	6.00E-04	3.330	28.140	3.480	111675	6207
Interior wall	498.29	7177	3.57E-04	1.430	13.510	2.290	119248	46265
Interior partition wall	93.84	2492	1.24E-04	0.630	5.470	0.980	42063	20333
Interior wall basement	52.46	1708	2.87E-05	0.290	2.320	0.310	13927	669
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	24.00	4698	1.10E-04	1.000	7.290	0.900	46503	1177
Wooden roof	204.00	-5549	4.59E-04	4.070	24.340	4.840	32389	543547
Concrete ceiling with parquet floor	612.67	46312	2.70E-03	19.238	170.475	23.220	676663	671229
Concrete ceiling bathroom	55.61	5951	2.12E-04	1.574	14.204	1.835	59090	33123
Basement ceiling with parquet floor	121.62	3438	1.03E-03	5.770	55.520	7.850	123839	443555
Concrete ceiling staircase	36.36	3092	1.22E-04	0.680	5.730	0.710	22756	1265
Basement ceiling entrance interior	19.90	563	1.68E-04	0.940	9.090	1.280	20263	72576
Basement ceiling entrance exterior	22.67	2024	7.85E-05	0.440	3.710	0.460	14590	796
Basement ceiling bathroom	13.82	1751	5.81E-05	0.450	4.010	0.520	17785	9055
Wooden balcony	99.69	-22137	6.33E-04	7.290	17.570	4.490	-146468	730650
Small window	6.37	752	4.21E-05	0.530	3.600	0.500	9180	3495
Medium window	10.83	1136	5.44E-05	0.710	5.380	0.750	13525	4362
Large window	54.88	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	9.89	859	2.42E-05	0.330	3.820	0.560	9905	1006
Apartment door	18.00	-177	1.22E-05	0.040	0.360	0.070	-593	8419
Balcony door	119.60	10410	3.00E-04	4.110	46.380	6.820	120028	12840
Basement interior door	8.00	303	1.22E-05	0.100	0.670	0.060	4022	231
Interior door	55.80	-608	4.19E-05	0.130	1.240	0.220	-2043	29000
Sum	**3707.85**	**261388**	**1.35E-02**	**100.531**	**797.079**	**111.325**	**3113212**	**2792879**

Table 76: Results for embodied impact, Concretecube, CAALA

Name	Area [m²]	GWP [kg CO²e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	713.58	87343	2.73E-03	24.163	176.773	24.033	1058600	36031
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123980	6763
Exterior wall staircase above roof	14.05	1996	4.50E-05	0.722	6.606	0.884	21671	25598
Interior wall staircase	259.87	27914	1.11E-03	6.130	51.775	6.405	205442	11419
Interior wall staircase basement	52.73	6045	2.00E-04	1.679	14.817	1.878	53154	33395
Interior wall elevator	137.56	15392	6.09E-04	3.378	28.545	3.530	113284	6296
Interior wall	549.62	7916	3.94E-04	1.577	14.902	2.526	131531	51031
Interior partition wall	100.71	2675	1.33E-04	0.676	5.871	1.052	45144	21822
Interior wall basement	62.91	2049	3.40E-05	0.348	2.782	0.372	16702	802
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	25.14	4921	1.15E-04	1.048	7.637	0.943	48714	1233
Wooden roof	202.87	-5518	4.56E-04	4.047	24.205	4.813	32209	540534
Concrete ceiling with parquet floor	736.35	57260	3.34E-03	23.786	210.776	28.709	836627	829908
Concrete ceiling bathroom	63.71	6817	2.42E-04	1.803	16.272	2.102	67693	37946
Basement ceiling with parquet floor	156.21	4416	1.32E-03	7.411	71.309	10.082	159056	569692
Concrete ceiling staircase	36.16	3075	1.21E-04	0.676	5.698	0.706	22630	1258
Basement ceiling entrance interior	11.21	317	9.50E-05	0.529	5.120	0.721	11413	40878
Basement ceiling entrance exterior	21.15	1889	7.30E-05	0.411	3.461	0.429	13612	743
Basement ceiling bathroom	16.74	2121	7.00E-05	0.545	4.857	0.630	21540	10967
Wooden balcony	90.68	-20136	5.76E-04	6.631	15.982	4.084	-133228	664603
Small window	6.37	752	4.20E-05	0.530	3.600	0.500	9180	3495
Medium window	10.83	1136	5.40E-05	0.710	5.380	0.750	13525	4362
Large window	54.88	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	9.89	859	2.40E-05	0.332	3.819	0.561	9905	1006
Apartment door	18.21	-179	1.20E-05	0.040	0.364	0.071	-600	8518
Balcony door	128.57	11190	3.23E-04	4.418	49.859	7.332	129030	13803
Basement interior door	8.09	306	1.20E-05	0.101	0.678	0.061	4069	234
Interior door	55.80	-608	4.20E-05	0.130	1.240	0.220	-2043	29000
Sum	**3954.93**	**279897**	**1.45E-02**	**106.527**	**857.055**	**119.314**	**3344380**	**2981113**

Table 77: Differences of embodied impact, Concretecube, Hartwig - CAALA

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	3472.51	1.09E-04	0.961	7.028	0.955	42089.43	1432.51
Exterior wall basement	-0.19	0.00E+00	0.000	0.000	0.000	-1.35	-0.07
Exterior wall staircase above roof	850.27	1.94E-05	0.308	2.814	0.376	9233.61	10906.74
Interior wall staircase	-5555.81	-2.20E-04	-1.220	-10.305	-1.275	-40889.61	-2272.69
Interior wall staircase basement	5.31	0.00E+00	0.001	0.013	0.002	46.66	29.32
Interior wall elevator	-218.64	-9.00E-06	-0.048	-0.405	-0.050	-1609.12	-89.44
Interior wall	-739.24	-3.70E-05	-0.147	-1.392	-0.236	-12283.32	-4765.59
Interior partition wall	-182.51	-9.00E-06	-0.046	-0.401	-0.072	-3080.59	-1489.14
Interior wall basement	-340.39	-5.30E-06	-0.058	-0.462	-0.062	-2775.19	-133.31
Bottom slab	0.00	0.00E+00	0.000	0.000	0.000	0.00	0.00
Roof above staircase	-223.32	-5.00E-06	-0.048	-0.347	-0.043	-2210.68	-55.95
Wooden roof	-30.76	3.00E-06	0.023	0.135	0.027	179.56	3013.28
Concrete ceiling with parquet floor	-10948.10	-6.38E-04	-4.548	-40.300	-5.489	-159963.29	-158678.60
Concrete ceiling bathroom	-866.46	-3.04E-05	-0.229	-2.068	-0.267	-8603.67	-4822.84
Basement ceiling with parquet floor	-977.72	-2.93E-04	-1.641	-15.789	-2.232	-35217.01	-126137.01
Concrete ceiling staircase	17.17	1.00E-06	0.004	0.032	0.004	126.35	7.02
Basement ceiling entrance interior	245.70	7.30E-05	0.411	3.970	0.559	8850.00	31698.05
Basement ceiling entrance exterior	135.67	5.50E-06	0.029	0.249	0.031	977.80	53.35
Basement ceiling bathroom	-369.70	-1.19E-05	-0.095	-0.847	-0.110	-3755.18	-1911.90
Wooden balcony	-2001.06	5.70E-05	0.659	1.588	0.406	-13239.89	66046.68
Small window	0.00	1.00E-07	0.000	0.000	0.000	0.00	0.00
Medium window	0.00	4.00E-07	0.000	0.000	0.000	0.00	0.00
Large window	0.00	0.00E+00	0.000	0.000	0.000	0.00	0.00
Entrance door	0.00	2.00E-07	-0.002	0.001	-0.001	0.11	-0.14
Apartment door	2.07	2.00E-07	0.000	-0.004	-0.001	6.96	-98.77
Balcony door	-780.72	-2.30E-05	-0.308	-3.479	-0.512	-9002.10	-963.00
Basement interior door	-3.55	2.00E-07	-0.001	-0.008	-0.001	-47.18	-2.71
Interior door	0.00	-1.00E-07	0.000	0.000	0.000	0.00	0.00
Sum	**-18509.47**	**-1.01E-03**	**-5.997**	**-59.976**	**-7.990**	**-231167.71**	**-188234.23**

Table 78: Deviation of embodied impact, Concretecube, Hartwig - CAALA

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg $PO_4{}^3e$]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	3.824	3.825	3.824	3.824	3.824	3.824	3.824
Exterior wall basement	-0.001	0.000	-0.001	-0.001	-0.001	-0.001	-0.001
Exterior wall staircase above roof	29.877	30.124	29.877	29.877	29.877	29.877	29.877
Interior wall staircase	-24.849	-24.859	-24.849	-24.849	-24.849	-24.849	-24.849
Interior wall staircase basement	0.088	0.000	0.088	0.088	0.088	0.088	0.088
Interior wall elevator	-1.441	-1.500	-1.441	-1.441	-1.441	-1.441	-1.441
Interior wall	-10.301	-10.364	-10.301	-10.301	-10.301	-10.301	-10.301
Interior partition wall	-7.324	-7.258	-7.324	-7.324	-7.324	-7.324	-7.324
Interior wall basement	-19.927	-18.467	-19.927	-19.927	-19.927	-19.927	-19.927
Bottom slab	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Roof above staircase	-4.754	-4.545	-4.754	-4.754	-4.754	-4.754	-4.754
Wooden roof	0.554	0.654	0.554	0.554	0.554	0.554	0.554
Concrete ceiling with parquet floor	-23.640	-23.625	-23.640	-23.640	-23.640	-23.640	-23.640
Concrete ceiling bathroom	-14.560	-14.342	-14.560	-14.560	-14.560	-14.560	-14.560
Basement ceiling with parquet floor	-28.438	-28.447	-28.438	-28.438	-28.438	-28.438	-28.438
Concrete ceiling staircase	0.555	0.820	0.555	0.555	0.555	0.555	0.555
Basement ceiling entrance interior	43.676	43.452	43.676	43.676	43.676	43.676	43.676
Basement ceiling entrance exterior	6.702	7.006	6.702	6.702	6.702	6.702	6.702
Basement ceiling bathroom	-21.114	-20.482	-21.114	-21.114	-21.114	-21.114	-21.114
Wooden balcony	9.039	9.005	9.039	9.039	9.039	9.039	9.039
Small window	0.000	0.238	0.000	0.000	0.000	0.000	0.000
Medium window	0.000	0.735	0.000	0.000	0.000	0.000	0.000
Large window	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Entrance door	0.000	0.826	-0.671	0.017	-0.157	0.001	-0.014
Apartment door	-1.173	1.639	-1.172	-1.173	-1.173	-1.173	-1.173
Balcony door	-7.500	-7.667	-7.500	-7.500	-7.500	-7.500	-7.500
Basement interior door	-1.173	1.639	-1.173	-1.173	-1.173	-1.173	-1.173
Interior door	0.000	-0.239	0.000	0.000	0.000	0.000	0.000
Sum	**-7.081**	**-7.515**	**-5.965**	**-7.525**	**-7.177**	**-7.425**	**-6.740**

Table 79: Results for embodied impact, Concretecube, CAALA modified

Name	Area [m²]	GWP [kg CO²e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	741.95	90815	2.84E-03	25.124	183.801	24.988	1100700	37464
Exterior wall basement	183.01	17203	6.67E-04	3.730	31.560	3.920	123979	6763
Exterior wall staircase above roof	20.04	2846	6.40E-05	1.030	9.420	1.260	30905	36505
Interior wall staircase	208.15	22358	8.85E-04	4.910	41.470	5.130	164552	9146
Interior wall staircase basement	52.78	6050	2.00E-04	1.680	14.830	1.880	53201	33424
Interior wall elevator	135.61	15174	6.00E-04	3.330	28.140	3.480	111675	6207
Interior wall	498.29	7177	3.57E-04	1.430	13.510	2.290	119248	46265
Interior partition wall	93.84	2492	1.24E-04	0.630	5.470	0.980	42063	20333
Interior wall basement	52.46	1708	2.90E-05	0.290	2.320	0.310	13927	669
Bottom slab	228.01	37507	1.45E-03	8.125	68.819	8.541	270313	14745
Roof above staircase	24.00	4698	1.10E-04	1.000	7.290	0.900	46503	1177
Wooden roof	204.00	-5549	4.59E-04	4.070	24.340	4.840	32389	543547
Concrete ceiling with parquet floor	612.67	46312	2.70E-03	19.238	170.475	23.220	676663	671229
Concrete ceiling bathroom	55.61	5951	2.12E-04	1.574	14.204	1.835	59090	33123
Basement ceiling with parquet floor	121.62	3438	1.03E-03	5.770	55.520	7.850	123839	443555
Concrete ceiling staircase	36.36	3092	1.22E-04	0.680	5.730	0.710	22756	1265
Basement ceiling entrance interior	19.90	563	1.68E-04	0.940	9.090	1.280	20263	72576
Basement ceiling entrance exterior	22.67	2024	7.80E-05	0.440	3.710	0.460	14590	796
Basement ceiling bathroom	13.82	1751	5.80E-05	0.450	4.010	0.520	17785	9055
Wooden balcony	99.69	-22137	6.33E-04	7.290	17.570	4.490	-146468	730650
Small window	6.37	752	4.20E-05	0.530	3.600	0.500	9180	3495
Medium window	10.83	1136	5.40E-05	0.710	5.380	0.750	13525	4362
Large window	54.88	5240	2.08E-04	2.850	24.350	3.460	61226	15032
Entrance door	9.89	859	2.40E-05	0.332	3.819	0.561	9905	1006
Apartment door	18.00	-177	1.20E-05	0.040	0.360	0.070	-593	8419
Balcony door	119.60	10410	3.00E-04	4.110	46.380	6.820	120028	12840
Basement interior door	8.00	303	1.20E-05	0.100	0.670	0.060	4022	231
Interior door	55.80	-608	4.20E-05	0.130	1.240	0.220	-2043	29000
Sum	**3707.85**	**261388**	**1.35E-02**	**100.533**	**797.078**	**111.326**	**3113223**	**2792879**

Table 80: Differences of embodied impact, Concretecube, Hartwig – CAALA modified

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	0.000	-4.29E-07	0.000	0.000	0.000	-10.572	0.000
Exterior wall basement	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Exterior wall staircase above roof	0.000	4.00E-07	0.000	0.000	0.000	0.000	0.000
Interior wall staircase	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall staircase basement	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall elevator	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior partition wall	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Interior wall basement	0.000	-3.00E-07	0.000	0.000	0.000	0.000	0.000
Bottom slab	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Roof above staircase	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Wooden roof	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Concrete ceiling with parquet floor	0.000	1.10E-07	0.000	0.000	0.000	0.000	0.000
Concrete ceiling bathroom	0.000	-3.54E-07	0.000	0.000	0.000	0.000	0.000
Basement ceiling with parquet floor	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Concrete ceiling staircase	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance interior	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance exterior	0.000	5.00E-07	0.000	0.000	0.000	0.000	0.000
Basement ceiling bathroom	0.000	1.00E-07	0.000	0.000	0.000	0.000	0.000
Wooden balcony	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Small window	0.000	1.00E-07	0.000	0.000	0.000	0.000	0.000
Medium window	0.000	4.00E-07	0.000	0.000	0.000	0.000	0.000
Large window	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Entrance door	-0.002	2.00E-07	-0.002	0.001	-0.001	0.108	-0.129
Apartment door	0.000	2.00E-07	0.000	0.000	0.000	0.000	0.000
Balcony door	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Basement interior door	0.000	2.00E-07	0.000	0.000	0.000	0.000	0.000
Interior door	0.000	-1.00E-07	0.000	0.000	0.000	0.000	0.000
Sum	**-0.002**	**1.03E-06**	**-0.002**	**0.001**	**-0.001**	**-10.464**	**-0.129**

Table 81: Deviation of embodied impact, Concretecube, Hartwig – CAALA modified

Name	GWP [kg CO^2e]	ODP [kg R11e]	POCP [kg C_2H_4e]	AP [kg SO_2e]	EP [kg PO_4^3e]	PENRT [MJ]	PERT [MJ]
Concrete exterior wall	0.000	-0.015	0.000	0.000	0.000	-0.001	0.000
Exterior wall basement	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Exterior wall staircase above roof	0.000	0.621	0.000	0.000	0.000	0.000	0.000
Interior wall staircase	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall staircase basement	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall elevator	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior partition wall	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Interior wall basement	0.000	-1.045	0.000	0.000	0.000	0.000	0.000
Bottom slab	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Roof above staircase	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Wooden roof	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Concrete ceiling with parquet floor	0.000	0.004	0.000	0.000	0.000	0.000	0.000
Concrete ceiling bathroom	0.000	-0.167	0.000	0.000	0.000	0.000	0.000
Basement ceiling with parquet floor	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Concrete ceiling staircase	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance interior	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement ceiling entrance exterior	0.000	0.637	0.000	0.000	0.000	0.000	0.000
Basement ceiling bathroom	0.000	0.172	0.000	0.000	0.000	0.000	0.000
Wooden balcony	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Small window	0.000	0.238	0.000	0.000	0.000	0.000	0.000
Medium window	0.000	0.735	0.000	0.000	0.000	0.000	0.000
Large window	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Entrance door	0.000	0.826	-0.633	0.016	-0.148	0.001	-0.013
Apartment door	0.000	1.639	0.000	0.000	0.000	0.000	0.000
Balcony door	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Basement interior door	0.000	1.639	0.000	0.000	0.000	0.000	0.000
Interior door	0.000	-0.239	0.000	0.000	0.000	0.000	0.000
Sum	0.000	0.008	-0.002	0.000	-0.001	0.000	0.000

E. Data for Example 1

Physical properties of existing building

The physical properties of the existing building to be refurbished are shown in Table 82.

Table 82: Physical properties of exisiting building

Component	Layers	Thickness [m]	λ [W/mK]	U-value
Exterior wall	Lime sand plaster	0.020	0.800	1.77
	Brick	0.300	0.860	
	Lime plaster	0.015	0.700	
Roof living area	Roof tiles	0.020	1.000	2.22
	Wood beams / air	0.120	0.621	
	Gypsum board	0.025	0.250	
Roof unconditioned	Roof tiles	0.020	1.000	2.22
	Wood beams /air	0.120	0.621	
	Gypsum board	0.025	0.250	
Uppermost ceiling	Wooden floor	0.030	0.130	0.89
	Wood beams / filling	0.260	0.571	
	Wooden cladding	0.030	0.130	
Basement ceiling	Wooden floor	0.030	0.130	0.87
	Wood beams / filling	0.265	0.569	
	Brick	0.115	0.860	
Window	Double glazing 4/16/4			2.8

Combined data

The combined data including physical properties, environmental data and RSL for insulation materials employed for possible refurbishment solutions are provided in Table 83. Table 84 provides the combined data for the windows and Table 85 the environmental data for energy carriers.

Table 83: Combined data for insulation materials

Insulation	Unit	Physical properties		Environmental data A1-A3 + C3-C4									RSL
				PET	PERT	PENRT	GWP	ODP	AP	EP	POCP	ADPE	
		ρ	λ	[MJ]	[MJ]	[MJ]	[kg CO2-eqv.]	[kg R11-eqv.]	[kg SO2-eqv.]	[kg PO43-eqv.]	[kg C2H4-eqv.]	[kg Sb-eqv.]	[a]
EPS	1 kg	15.5	0.035	85.78	0.54	85.24	2.99	9.9E-08	0.00645	0.00068	0.01677	5.4E-07	40
XPS	1 kg	32.0	0.035	97.65	1.97	95.68	3.27	1.7E-05	0.00690	0.00064	0.00285	0.00086	40
PUR	1 kg	30.0	0.030	93.88	1.63	92.25	4.47	7.3E-08	0.01417	0.00147	0.00237	0.00034	40
GW	1 kg	60.0	0.035	31.57	2.43	29.14	1.80	3.8E-09	0.00366	0.00063	0.00042	7.0E-05	40
SW	1 kg	90.0	0.040	16.41	2.45	13.96	0.92	3.6E-08	0.00682	0.00116	0.00042	2.5E-07	40
FG	1 kg	117.0	0.042	28.86	8.80	20.05	1.30	4.2E-10	0.00282	0.00035	0.00024	7.1E-06	40
WFIB	1 kg	200.0	0.040	36.12	22.87	13.26	-1.55	1.8E-06	0.00117	0.00015	0.00025	1.2E-07	40
CIB	1 kg	80.0	0.040	44.82	16.10	28.72	0.85	9.4E-06	0.00636	0.00125	0.00046	0.00023	40
VIP	1 kg	145.0	0.007	235.97	47.85	188.11	9.33	1.3E-06	0.02989	0.00299	0.00253	0.00034	30

Table 84: Combined data for windows

Window	Unit	Physical properties		Environmental data A1-A3 + C3-C4									RSL
				PET	PERT	PENRT	GWP	ODP	AP	EP	POCP	ADPE	
		U	g	[MJ]	[MJ]	[MJ]	[kg CO2-eqv.]	[kg R11-eqv.]	[kg SO2-eqv.]	[kg PO43-eqv.]	[kg C2H4-eqv.]	[kg Sb-eqv.]	[a]
Double PVC-U	1 m²	1.30	0.60	1314.2	45.40	1268.8	70.59	3.1E-06	0.34672	0.07527	0.02010	0.00214	40
Triple PVC-U	1 m²	0.80	0.50	1533.2	52.63	1480.5	84.19	3.6E-06	0.40237	0.07875	0.02399	0.00235	40
Double wood	1 m²	1.30	0.60	866.9	266.88	599.9	31.92	7.3E-07	0.17873	0.03050	0.02782	0.00087	40
Triple wood	1 m²	0.80	0.50	1085.9	274.12	811.8	45.53	1.3E-06	0.23438	0.03399	0.03170	0.00108	40

Table 85: Environmental data of energy carriers

Energy carrier	Unit	Environmental data B6								
		PET	PERT	PENRT	GWP	ODP	AP	EP	POCP	ADPE
		[MJ]	[MJ]	[MJ]	[kg CO2-eqv.]	[kg R11-eqv.]	[kg SO2-eqv.]	[kg PO43-eqv.]	[kg C2H4-eqv.]	[kg Sb-eqv.]
Gas	1 kWh	4.29	0.01	4.28	0.2606	1.1E-11	0.00021	3E-05	3.3E-05	1.3E-08
Electricity mix	1 kWh	10.26	1.49	8.77	0.6230	3.1E-09	0.00103	9.9E-05	7.6E-05	5.1E-08
Electricity wind	1 kWh	9.15	9.01	0.14	0.0118	4.1E-11	0.00003	2.5E-06	4.5E-06	-2.2E-07

Data for supplementary example of multi-criteria optimization

Table 86: GWP and costs of insulation materials

Insulation materials	ρ [kg/m³]	λ_i [W/mK]	C [J/kg K]	GWP [kg CO_2-e/m³]	Cost [€/m³]
Glass wool (GW30)	30	0.035	810	45.2	88.00
Glass wool (GW50)	50	0.032	810	75.3	152.00
Glass wool (GW100)	100	0.035	810	150.6	285.00
Stone wool (SW40)	40	0.035	1030	52.0	143.80
Stone wool (SW50)	50	0.400	1030	104.0	269.00
Stone wool (SW100)	100	0.036	1030	124.8	226.00
Stone wool (SW34)	34	0.036	1030	156.0	196.50
Expanded polystyrene (EPS15)	15	0.038	1400	110.4	112.00
Expanded polystyrene (EPS30)	30	0.035	1500	220.9	174.00
Polyurethane foam (PUR)	30	0.027	1480	203.6	250.00
Wood fibre insulation board (WFIB50)	50	0.039	2100	21.6	150.00
Wood fibre insulation board (WFIB110)	110	0.040	2100	47.5	272.00
Wood fibre insulation board (WFIB140)	140	0.043	2100	60.4	299.00
Wood fibre insulation board (WFIB190)	190	0.045	2100	77.7	410.00
Cellulose (CE)	50	0.040	2150	19.6	100.00
Calcium silicate (CS115)	115	0.046	1300	48.4	339.00
Hemp fibre insulation board (HE)	40	0.040	1600	3.1	170.00
Vacuum insulation panels (VIP)	200	0.007	800	744.0	7500.00
Phenolic foam board (PF)	40	0.023	1400	260.3	335.00

Table 87: GWP and costs for types of constructions

Construction	RSL [a]	ΔGWP [kg CO_2-e/m²]	GWP'(d) [kg CO_2-e/m³]	Cost [€/m²]	Cost(d) [€/m³]
Interior Insulation vapour barrier (INTVB)	30	5.04	3.12	55.00	28.00
Interior Insulation capillary active (INTCA)	30	6.60	0.00	70.00	0.00
Exterior thermal insulation composite systems (ETICS)	30	11.00	0.00	85.00	0.00
Ventilated façade, wood cladding, wood substructure (VFW)	40	0.75	3.12	100.00	28.00
Ventilated façade, fibre cement cladding, aluminium substructure (VFA)	40	21.22	2084.88	115.00	20.00
Double brick cavity wall (DBCW)	60	59.00	0.00	135.00	0.00

F. Data for Example 2

Table 88: Heating system 1, gas fuelled heat pump + floor heating

	Layer name	Name in Ökobau.dat	Amount
1	Gas fuelled heat pump (Air)	Gaswärmepumpe (Luft) 20-70 kW	157 kg
2	Floor heating	Fußbodenheizung PP (200 mm Abstand)	1/1 m²

Table 89: Heating system 2, electricity powered heat pump (earth) + floor heating

	Layer name	Name in Ökobau.dat	Amount
1	Electricity powered heat pump (earth)	Strom-Wärmepumpe (Sole-Wasser, Erdkollektor) 20 kW	4692 kg
2	Floor heating	Fußbodenheizung PP (200 mm Abstand)	1/1 m²

Table 90: Heating system 3, gas condensing boiler + floor heating

	Layer name	Name in Ökobau.dat	Amount
1	Gas condensing boiler	Gas-Brennwertgerät 20-120 kW (Standgerät)	283 kg
2	Floor heating	Fußbodenheizung PP (200 mm Abstand)	1/1 m²

Table 91: Heating system 4, gas condensing boiler + radiators

	Layer name	Name in Ökobau.dat	Amount
1	Gas condensing boiler	Gas-Brennwertgerät 20-120 kW (Standgerät)	283 kg
2	Radiator	Heizkörper Typ 22 h=600mm	1/20 m²

Table 92: Heating system 5, wood chip boiler + floor heating

	Layer name	Name in Ökobau.dat	Amount
1	Wood chip boiler	Hackschnitzelkessel 20-120 kW	921 kg
2	Floor heating	Fußbodenheizung PP (200 mm Abstand)	1/1 m²

Table 93: Heating system 6, district heating + floor heating

	Layer name	Name in Ökobau.dat	Amount
1	District heating	Übergabestation Fernwärme	20 kg
2	Floor heating	Fußbodenheizung PP (200 mm Abstand)	1/1 m²

Table 94: Overview of building material combinations

Variant	Exterior wall	Roof	Ceiling	Interior wall	Slab
M1: ETICS	3: ETICS	1: Concrete	1: Concrete	2: Lime-sand stone	1: Concrete
M2: Brick	1: Poroton	1: Concrete	1: Concrete	3: Brick	1: Concrete
M3: Concrete	4: Concrete	1: Concrete	1: Concrete	1: Concrete	1: Concrete
M4: Wood	12: Wood frame	3: Wooden beams	6: Wooden beams	4: Wood frame	1: Concrete
M5: Ventilated facade	6: Ventilated facade	1: Concrete	1: Concrete	2: Lime-sand stone	1: Concrete
M6: Double shell	14: Double shell	3: Wooden beams	1: Concrete	4: Wood frame	1: Concrete

Table 95: Exterior wall 1, Poroton

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Plaster	Oberputze Leichtputz RK 2mm - Alligator	2.00		
2	Insulated brick	Mineralwollgefüllte Ziegel - Deutsche POROTON	16	26	51
3	Plaster	Oberputze Leichtputz RK 2mm - Alligator	2.00		

Table 96: Exterior wall 3, external thermal insulation composite systems (ETICS) on lime sand stone

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Plaster	Kunstharzputz - VDL	0.20		
2	Fibre glas reinforcement grid	Glasarmierungsgitter - Vitrulan	0.05		
3	Synthetic resin	Armierung (Kunstharzspachtel)	0.04		
4	EPS	EPS PS 15	7	13	25
5	Plaster	Armierung (Kunstharzspachtel)	0.20		
6	Lime sand stone	Kalksandstein - Bundesverband Kalksandstein	24.00		
7	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)	1.50		

Table 97: Exterior wall 4, concrete

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Plaster	Kunstharzputz - VDL	0.20		
2	Fibre glas reinforcement grid	Glasarmierungsgitter - Vitrulan	0.05		
3	Synthetic resin	Armierung (Kunstharzspachtel)	0.04		
4	EPS	EPS PS 15	8	13	26
5	Synthetic resin	Armierung (Kunstharzspachtel)	0.20		
6	Concrete C20/25	Transportbeton C20/25	15.00		
7	Reinforcement	Bewehrungsstahl	0.3 (2 Vol%)*		

Table 98: Exterior wall 6, ventilated facade

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Wooden cladding	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	2.40		
2	Wooden laths 40/60 mm	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	0.048*		
3	Sheathing membrane	Unterspannbahn PP	0.08		
4	Rock wool	Steinwolle Flachdachdämmplatte (140 mm)	6	11	23
5	Lime sand stone	Kalksandstein - Bundesverband Kalksandstein	24.00		
6	Plaster	Oberputze Leichtputz K2-3mm, RK 3mm - Alligator	1.50		

Table 99: Exterior wall 12, wood frame

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Wooden cladding	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	0.20		
2	Wooden laths 40/60 mm	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	0.048*		
3	Wood fibre board	Holzfaserplatte DFF - Egger	3.00		
4	Gypsum plaster board	Gipskartonplatte (Brandschutz)	0.95		
5	Wooden beam 12/18 cm	Schnittholz Fichte (12% Feuchte/10,7% H2O)	2.16*		
6	Wood fibre insulation board	Holzfaserdämmplatte (Trockenverfahren) Thermowall-gf - GUTEX	5	11	26
7	OSB board	OSB Eurostrand - Egger	1.80		
8	Gypsum plaster board	Gipskartonplatte	1.50		

Table 100: Exterior wall 14, double shell

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Facing brick	Vormauerziegel	12.50		
2	Cellulose insulation boards	Zellulosefaserplatten	1	6	17
3	Brick	Mauerziegel Durchschnitt - Poroton	24.00		
4	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)	1.50		

Table 101: Roof 1, concrete

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Gravel 2/32	Kies 2/32 getrocknet	4.00		
2	Bitumen sheeting	Bitumenbahnen G 200 S4	0.80		
3	XPS	XPS-Dämmstoff	12	18	25
4	Vapor barrier PA	Dampfbremse PA	0.30		
5	Concrete C20/25	Transportbeton C25/30	20.00		
6	Reinforcement	Bewehrungsstahl	0.8 (4 Vol%)*		
7	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)	1.50		

Table 102: Roof 3, wooden beams

	Layer name	Name in Ökobau.dat	Thickness [cm]		
1	Bitumen sheeting	Bitumenbahnen G 200 S4	0.80		
2	Wood fibre insulation board	Holzfaserdämmplatte (Trockenverfahren) Thermosafe-homogen - GUTEX	12	18	25
3	Vapor barrier PA	Dampfbremse PA	0.30		
4	Wooden planking	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	2.40		
5	Wooden beam 12/18 cm	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	2.16*		

Table 103: Slab 1, concrete

	Layer name	Name in Ökobau.dat	Thickness [cm]
1	Tiles	Steinzeugfliesen glasiert	1.00
2	Tile adhesive	Fliesenkleber	0.80
3	Cement screed	Zementestrich - IWM	6.00
4	Vapor barrier PE	Dampfbremse PE	0.02
5	XPS	XPS-Dämmstoff	6 / 10 / 25
6	Bitumen sheeting	Bitumenbahnen G 200 S4	0.40
7	Concrete C20/25	Transportbeton C25/30	25.00
8	Reinforcement	Bewehrungsstahl	1.00 (4 Vol%)*
9	Lean concrete	Transportbeton C25/30	8.00

Table 104: Ceiling 1, concrete

	Layer name	Name in Ökobau.dat	Thickness [cm]
1	Tiles	Steinzeugfliesen glasiert	1.00
2	Tile adhesive	Fliesenkleber	0.80
3	Cement screed	Zementestrich - IWM	6.00
4	Vapor barrier PE	Dampfbremse PE	0.02
5	Concrete C20/25	Transportbeton C25/30	18.00
6	Reinforcement	Bewehrungsstahl	0.72 (4 Vol%)*
7	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)	1.50

Table 105: Ceiling 6, wooden beams

	Layer name	Name in Ökobau.dat	Thickness [cm]
1	Parquet floor	Stabparkett	2.00
2	Dry screed	Trockenestrich (Gipsfaserplatte)	2.50
3	Wood fibre footstep sound insulation	Holzfaserdämmplatte (Trockenverfahren) Thermosafe-homogen - GUTEX	2.00
4	Chipboard	Spanplatte (Durchschnitt)	2.50
5	Wood beam 12/18 cm	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	2.16
6	Vapor barrier PE	Dampfbremse PE	0.02
7	Wooden laths 30/60 mm	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	0.036*
8	Wooden cladding	Schnittholz Fichte (12% Feuchte/10,7% H_2O)	2.40

Table 106: Interior wall 1, concrete

	Layer name	Name in Ökobau.dat	Thickness [cm]	
1	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)		1.50
2	Concrete C20/25	Transportbeton C25/30	15.00	10.00
3	Reinforcement (2 %)	Bewehrungsstahl	0.30*	0.20*
4	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)		1.50

Table 107: Interior wall 2, lime sand stone

	Layer name	Name in Ökobau.dat	Thickness [cm]	
1	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)		1.50
2	Lime sand stone	Kalksandstein - Bundesverband Kalksandstein	17.50	11.50
3	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)		1.50

Table 108: Interior wall 3, brick

	Layer name	Name in Ökobau.dat	Thickness [cm]	
1	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)		1.50
2	Brick	Mauerziegel Durchschnitt - Poroton	17.50	11.50
3	Gypsum plaster	Gipsputz (Gips-Kalk-Putz)		1.50

Table 109: Interior wall 4, wood frame

	Layer name		Name in Ökobau.dat	Thickness [cm]	
1	OSB board		OSB Eurostrand - Egger		1.80
2	Wooden beam 6/10 cm	Wooden beam 6/8cm	Schnittholz Fichte (12% Feuchte/10,7% H2O)	3.75*	3.00*
3	Rock wool		Steinwolle Flachdachdämmplatte (140 mm)		7.50
7	OSB board		OSB Eurostrand - Egger		0.90