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Design Catalogue in a CAE Environment for the Illustration of Tailored Forming

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ABSTRACT

Tailored Forming, which is explored in the Collaborative Research Centre 1153 at the Leibniz University Hannover, is a highly sophisticated set of manufacturing technologies that allow producing hybrid forming parts consisting of two different materials. In this paper, two elements of a computer-aided engineering environment are characterized that aims at assisting a designer in synthesis of such components. In order to determine the application potential of Tailored Forming, TRIZ-Reverse and its application is introduced. The resulting Tailored Forming Contradiction Matrix documents the Knowledge of Applicability for this manufacturing technology. Afterwards, design catalogues are discussed as repositories for detailed Tailored Forming Design Knowledge, exemplarily shown for drive components. Both then are integrated to a knowledge-based system that allows reasoning about the design of Tailored Forming components. The resulting concept then may be processed to a computer-aided design (CAD) system as starting point for detailed design, simulation and optimization.

Index Terms – Tailored Forming, Computer-Aided Engineering Environment, Design Catalogue, TRIZ Reverse

1. INTRODUCTION

Today's manufacturing processes offer great potential for creating feature and property optimized components for many different applications. As conventional mono-material solid components are reaching their technological limitations, the Collaborative Research Centre (CRC) 1153 "Process Chain for Manufacturing Hybrid High Performance Components by Tailored Forming" investigates a different approach. A Tailored Forming component consists of two different materials, e.g. steel and aluminum [1]. The resulting potential especially for light weight design is high.

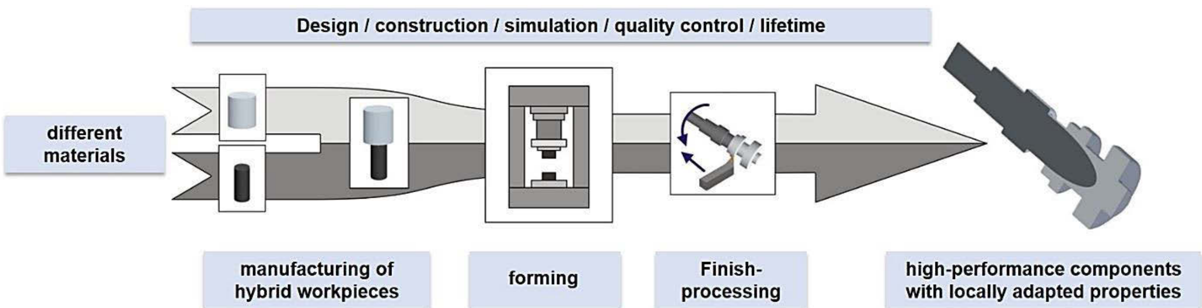


Figure 1: General process chain of Tailored Forming (acc. to [1])

The generic process chain is shown in Fig. 1. In the beginning, two semi-finished workpieces of different materials are joined by friction welding or ultrasonic assisted laser welding. After

that, the hybrid workpiece is shaped in a forming process. The last step is finish-processing by heat treatment and machining [1].
One field of application is drive parts. Regarding automotive engineering, the drive train offers tremendous potential for Tailored Forming since structurally unstressed parts of a component may be manufactured in aluminum whereas loaded parts are made by steel [2]. Since weight reduction of the entire vehicle is a mayor issue for increasing efficiency [e.g. 3, 4], and legislation calls for a distinct reduction of greenhouse gas emissions [e.g. 5, 6], the application of Tailored Forming is relevant.
In comparison to traditional manufacturing process chains, Tailored Forming is more sophisticated. Due to the mandatory forming process, geometry and material characteristics of the joining zone between both constituents are adjusted so that the mechanical properties like the stress distribution of the components change. In addition to that, many boundary conditions for the general applicability of the technology and explicit knowledge like manufacturing restrictions are not easily available. The first strongly depends on the prevailing load cases, the second to the availability of single manufacturing processes and their respective design guidelines [7]. In order to convey the necessary knowledge to a design engineer, one aspect of the CRC 1153 is to develop a computer aided engineering (CAE) environment for the design and optimization of Tailored Forming components. As CAE environment, the authors understand a toolbox for the development of domain-specific artifacts, which includes the necessary tools for all synthesis and analysis activities as well as their information technology interfaces and data storages.
In the following paper, two very basic elements of this CAE environment are characterized. In order to determine the application potential of Tailored Forming, TRIZ-Reverse and its application is introduced. The resulting Tailored Forming Contradiction Matrix documents the *Knowledge of Applicability* for this manufacturing technology. Afterwards, design catalogues are discussed as repositories for detailed Tailored Forming *Design Knowledge,* exemplarily shown for drive components. Both then are integrated to a rudimental knowledge-based system that allows reasoning about the design of Tailored Forming components. The resulting concept then may be processed to a computer-aided design (CAD) system as starting point for detailed design, simulation and optimization. The paper closes with a short overview of the remaining parts of the CAE environment and drafts further research.

2. KNOWLEDGE OF APPLICABILITY OF TAILORED FORMING

2.1 Background: TRIZ Contradiction Matrix

TRIZ (*Teoria reschenija isobretatjelskich sadatsch* - theory of inventive problem solving) is a collection of methods and tools for the systematic development of innovative products [8]. The confirmed hypothesis behind is that similar problems lead to similar solutions so the research of patents can reveal underlying solution patterns [9]. It was found that each of these solution patterns, which are named *Inventive Principles*, can be viewed as overcoming of an engineering contradiction. I.e., a moving object has to be of low weight but of high strength. Such contradictions were collected and systematically processed in the contradiction matrix, which is one of the most established TRIZ tools. Depending on the version of the matrix, 40 or more Innovative Principles are assigned to multiple parameters that have to be improved on the one side, but that also worse another parameter on the other side. Fig. 2 shows an excerpt of the matrix provided by Mann [10], which is used in this paper and distinguishes 50 parameters. As depicted above, the example is to improve parameter No. 1 “Weight of moving object” and accept decreasing parameter No. 20 “Strength”.

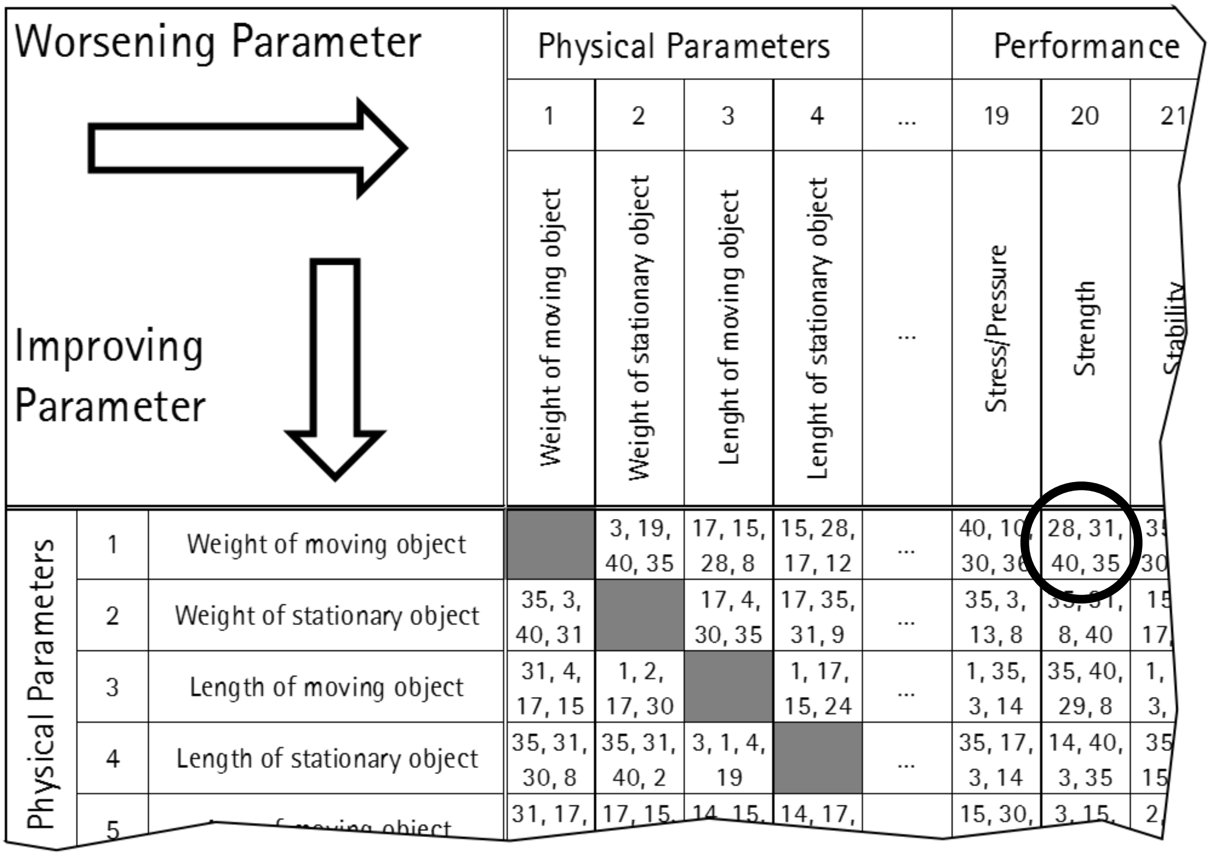


Figure 2: Part of the TRIZ contradiction matrix 2010 (acc. to [10])

In the crossing field of the matrix, each number codes one of the Inventive Principles, which is applicable in that situation. In that case it would be 28 (Mechanics Substitution), 31 (Porous Materials), 40 (Composite Materials), 35 (Parameter Changes), where the sequence refers to the probability of occurrence. In the next step, a designer has to translate these solution patterns to his actual design problem. The quality of the results strongly depends on expertise and experience of the designer since the principles are formulated in an abstract way to meet a large variety of applications. This process is shown in Fig. 3.

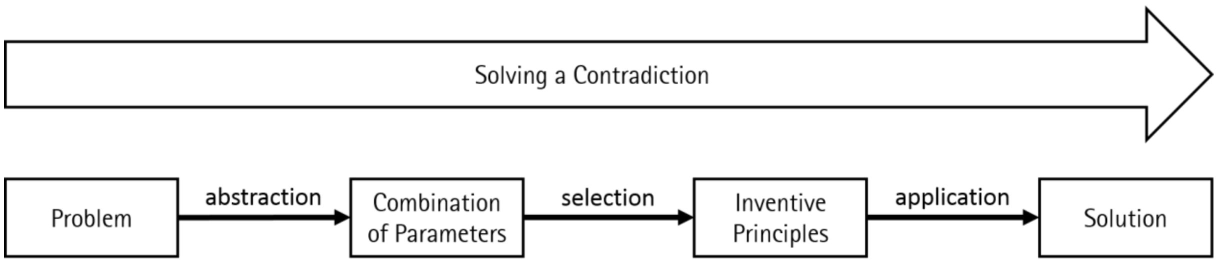


Figure 3: Solving a contradiction by using the contradiction matrix

2.2 TRIZ-Reverse

When the process shown in Fig. 3 is reversed, it can be used to assign solutions to abstracted problem statements corresponding to the Innovative Principles. Consequently, when a new process technology comes up its potential as solution to an engineering problem may be estimated by identifying the Innovative Principles that are realized by the technology as depicted in Fig. 4 [11].

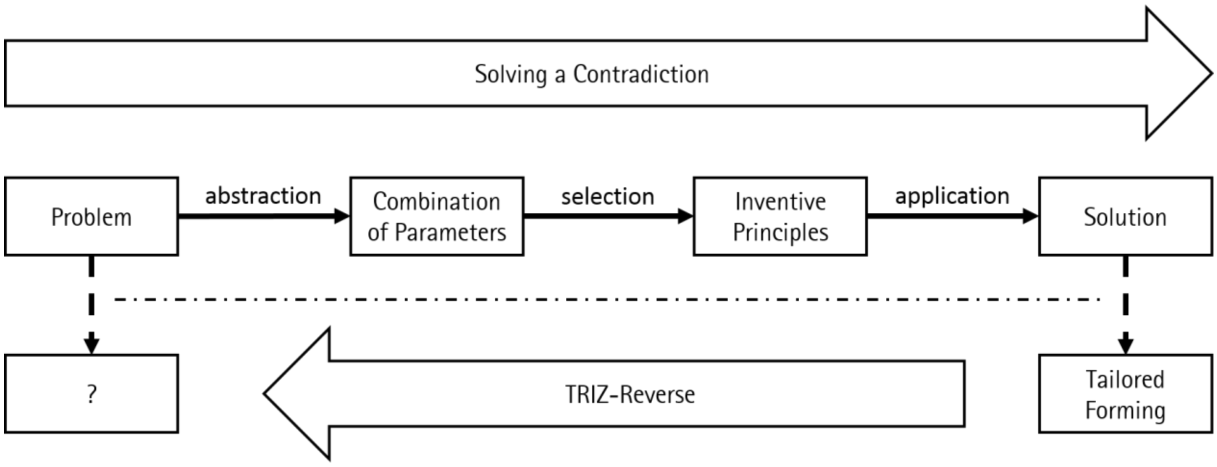


Figure 4: The process of solving a contradiction compared to TRIZ-Reverse

Applied to Tailored Forming, the analysis of the 40 existing principles showed four relevant ones:

- No 3: Local quality: If the structure of the object is homogeneous, it has to be changed to inhomogeneous. So every part of the object is adapted to the local conditions. A component which is basically made of aluminum to reduce the weight has parts made of steel to get a higher resistance against mechanical wear.
- No 6: Universality: This principle means that an object should perform multiple functions in order to eliminate other parts. I.e., if the object is formed out of two materials, it does not have to be assembled afterwards and both functions are combined in one component.
- No 11: Beforehand cushioning: For Tailored Forming a shaft with high rotation velocity is conceivable with a steel core and an aluminum coat. The coat reduces the weight and the inner core has a high strength. In case of a breaking coat, the inner core holds the component together.
- No 40: Composite materials: This is Tailored Forming per se.

In order to document the potential application of Tailored Forming manufacturing technologies, the original Contradiction Matrix can be filtered so that only the four relevant principles are shown. The resulting matrix (Figure 5) thus contains the *Knowledge of Applicability* of Tailored Forming.

Worsening Parameter → / Improving Parameter ↓			Physical Parameters					Performance		
			1	2	3	4	...	19	20	21
			Weight of moving object	Weight of stationary object	Lenght of moving object	Lenght of stationary object	...	Stress/Pressure	Strength	Stabilit
Physical Parameters	1	Weight of moving object		3, 40	40		...	40, 3	40	
	2	Weight of stationary object	3, 40		3	3	...	3, 40	40	
	3	Length of moving object					...	3	40, 3	3, 4
	4	Length of stationary object	40	40, 3	3		...	3	40, 3	3
	5	Area of moving object	3, 40	3			...	40	3, 40	40
	6	Area of stationary object	3		3	3	...	3, 40	40, 3	
	7	Volume of moving object	40	40	3	3	...	3, 40	40	
	8	Volume of stationary object	40, 3	40, 3	3		...	40	40	4
	9	Shape	3, 40	3, 40			...	3	40, 3	40
	10	Amount of substance	40, 6	40	3	3, 40	...	40, 3	40, 3	40
		Amount of information			3	3	...			3

Figure 5: Part of the TRIZ-Reverse Matrix applied for Tailored Forming

Note that TRIZ-Reverse is not to be confused with "Reverse TRIZ", an approach to detect failures of a system during early development stages, similar to the Failure Mode and Effects Analysis (FMEA) [e.g., 12].

3. DESIGN KNOWLEDGE FOR TAILORED FORMING

3.1 Background: Design Catalogues

The design catalog was introduced as information storage, especially developed for product development and there the early phase of the development process. It is ought to support design engineers in their tasks of acquiring new expertise, organize it and encourage them to derive and develop new solutions in a methodological way [13]. Depending on the type of knowledge that is documented in a specific catalogue, four generic types may be distinguished (Figure 6):

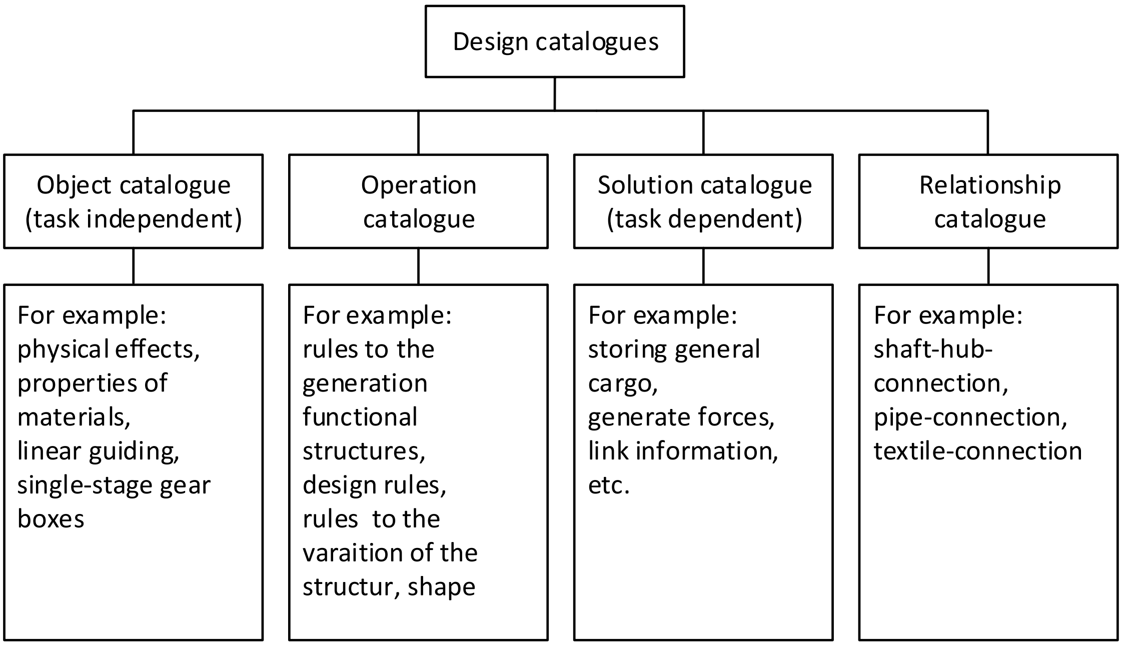


Figure 6: Types of Design Catalogs with different Application Examples (acc. to [14])

The object catalogue contains basic facts, especially of physical, geometrical, technological nature, which has to be task independent. Operation catalogues cover operations (process steps) or sequences of operations (methods) that are interesting with regard to design methodology. These include e.g. rules for synthesizing functional structures or solution variants. In contrast to object catalogues, the solution catalogue is a tool for structuring task dependent knowledge, e.g. different solution alternatives to a given design problem. At last, relationship catalogs are a special kind of solution catalog that describe the relationship between two specific objects which has to be understood as functional solution, e.g. shaft-hub connections [14].

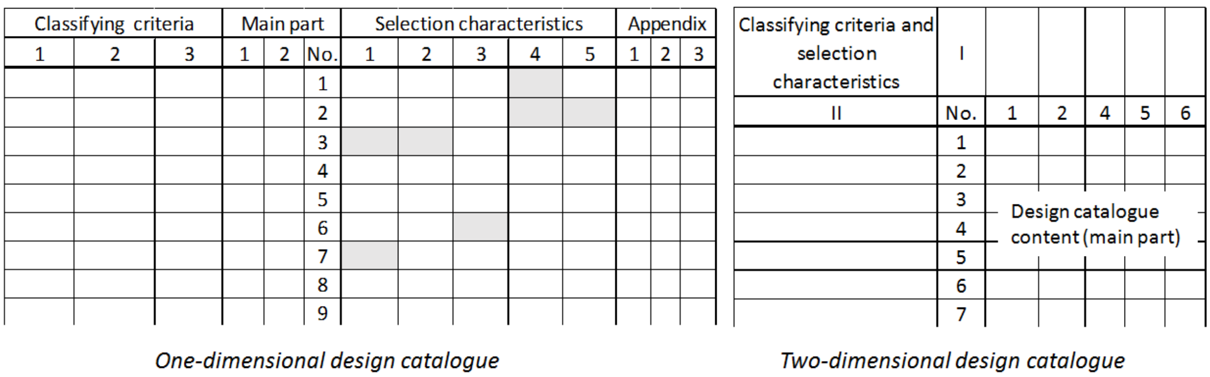


Figure 7: One- and two-dimensional design catalogues (acc. to [14])

The structure of design catalogues follows strict requirements which divide the catalog in basically three parts: (1) Classifying criteria serve as index structure, (2) the main parts contains descriptions of the solution in a suitable form and (3) selection characteristics that allow to access the content not via the index structure but other specific criteria that either describe or rate the solution. Optional, the catalogue may be extended by an appendix which contains any remarks. With respect to the manifold of index structures, one-, two- and three-dimensional catalogues have been implemented. The one-dimensional catalogue is the most common type and is set up like depicted left-hand side in Fig. 7. Also very common is a two-

dimensional catalogue as matrix representation of two index structures where the corresponding solutions are located in the crossing fields of the matrix. While the small space and high information density in such a catalogue is beneficial, the lack of additional selection characteristics is a disadvantage. Three-dimensional catalogues add multiple two-dimensional ones as layers [15, 16].
Although multiple approaches of computer-aided catalogue systems exist, no commercial application or software systems have been implemented so far. Nevertheless, the catalogue can serve as knowledge base for a knowledge-based engineering system since it is able to code case based task dependent engineering knowledge [17].

3.2 Knowledge Repository for Tailored Forming Design Knowledge

Design Knowledge for Tailored Forming has to link:

- Joining Zone Concepts (e.g. co-axial or serial arrangement of constituents)
- Design Guidelines (e.g. Design for Cross-Wedge-Rolling)
- Manufacturing Process Restrictions (e.g. forming temperatures, tool sizes, etc.)

At the current state of the research in the CRC 1153, the design knowledge will be discussed exemplified for drive components in a first step. Therefore, a design catalogue has been implemented that has the structure showed in fig. 8 below.

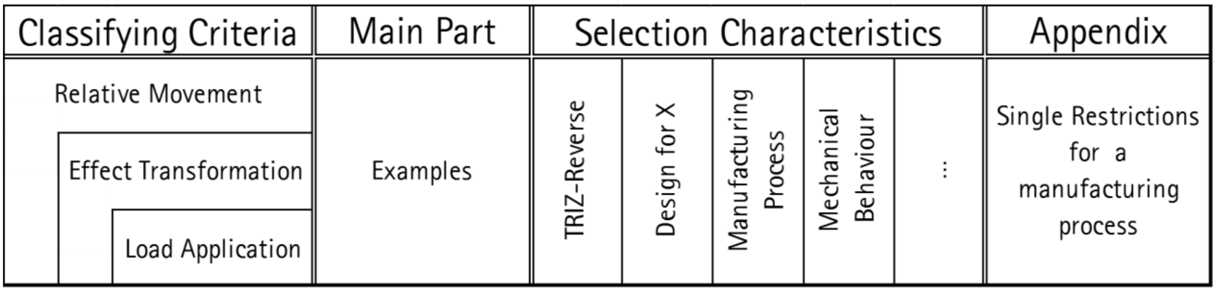


Figure 8: Structure of the Tailored Forming Object Catalogue

The classifying criteria contain at the first level the movement of a drive part, which can be static, rotating or oscillating. The second level differentiates different transformations of physical effects, e.g. the translation of force into torque or force into reaction forces. The third level describes the load application points. The main part illustrates the Tailored Forming components. It shows a picture of the traditional part design, sketches of the load cases and a Tailored Forming version of the part with information on the joining zone configuration. Classifying criteria and main part are exemplarily depicted in fig. 9.

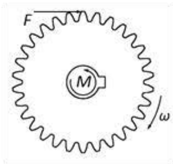
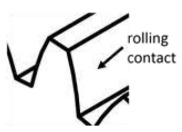
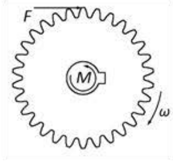
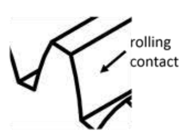
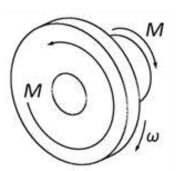
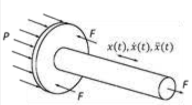
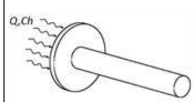
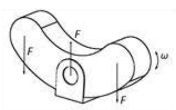
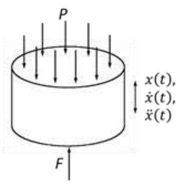
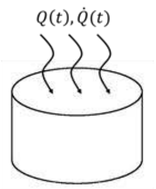
Classifying Criteria			Main Part				
Move-ment	Effect transformation	Number, points of origin	Component	Picture	Sketch of load cases	Sketch of other loads	Possible Tailored Forming solution
1	2	3	1	2	3	4	5
...	...	...	...	...	...	...	...
rotation	force - moment	2	spur-gear				
			bevel gear				
	moment - moment	2	wheel hub			--	
	...	...	...	...	...	...	...
oscillation	force - force	2	exhaust valve				
		3	rocker arm			--	
	pressure - force	2	piston				
	...	...	...	...	...	...	...

Figure 9: Tailored Forming Object Catalogue (Classifying Criteria and Main Part)

Regarding the selection characteristics, the input parameters of the Tailored Forming Contradiction Matrix are itemized. Since some solutions allow two different contradictions to be solved, two columns are designated for that. Afterwards, details for the load cases can be found. In the current version of the catalog these are markers what single loads have to be considered. The last part contains information about the involved manufacturing processes, for creating of the semi-finished parts as well as for the forming processes themselves (fig. 10).

Selection Characteristics																		
TRIZ-Reverse Input parameter (left, improving parameter - right, worsening parameter)				Load cases						Other loads					Manufacturing			
parameter combination I		parameter combination II		tensile	compres-sive	bending	torsion	shearing	buckling	mechanical wear	thermal	chemical	rolling contact	areas with-out load	joining process	forming process	number of forming stages	finishing
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
weight	loss of material						x			x			x		ultrasound assisted laser welding	die forging		heat treating, machining
weight	loss of material						x			x			x		ultrasound assisted laser welding	die forging		heat treating, machining
weight	strength						x							x	friction welding	die forging		heat treating, machining
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
weight	strength	tempera-ture	loss of material	x						x	x	x			friction welding	cross wedge rolling	2 - 3	heat treatment, machining
weight	strength			x	x	x				x			x		ultrasound assisted laser welding	die forging	3 - 4	heat treating, machining
weight	strength	tempera-ture	weight	x	x					x	x	x			friction welding	die forging	3 - 4	heat treatment, machining
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Figure 10: Tailored Forming Object Catalogue (Selection Characteristics)

Note, that the Tailored Forming Contradiction Matrix can be interpreted as two-dimensional design catalogue as well. As the contradictions and parameter combinations occur in both catalogues, they will be used as linking elements in the following computer aided engineering environment.

4. COMPUTER AIDED ENGINEERING ENVIRONMENT

The aim of the previously described mechanisms is to give access and convey knowledge about the applicability of tailored forming technologies to a designer. In the computer aided engineering environment set up within the framework of the CRC, the (partial) automatic design of a Tailored Forming component and its optimization are implemented with respect to a distinct application. Beside the knowledge bases, interfaces to a parametric CAD system and an implementation of FE / optimization tools have to be integrated to allow a closed loop between design, simulation and optimization. The main challenge here is that the components, which can be generated by Tailored Forming, are geometrically largely different from each other. In order to avoid creating a separate CAD template for each of the special cases in the catalogue, which can only be optimized to a limited extent, the Generative Design Approach is used. Here, the shape of a component is decomposed into individual pieces of parametrized geometry, which represent autonomous information carriers that contain control concepts and e.g. manufacturing restrictions. In this way, these so called *design elements* can be adapted to a large variety of changing requirements. For further information on the modeling approach please refer to [18].

Fig. 11 shows the desired sequence of the development of a Tailored Forming component in the CAE environment. In the first step, the Tailored Forming Contradiction Matrix is used to formulate concepts for the engineering contradiction to solve the specific design problem in an abstract way. These must be complemented by the function description and the requirements for the specific component. On this basis, a suitable draft is output by the design catalog.

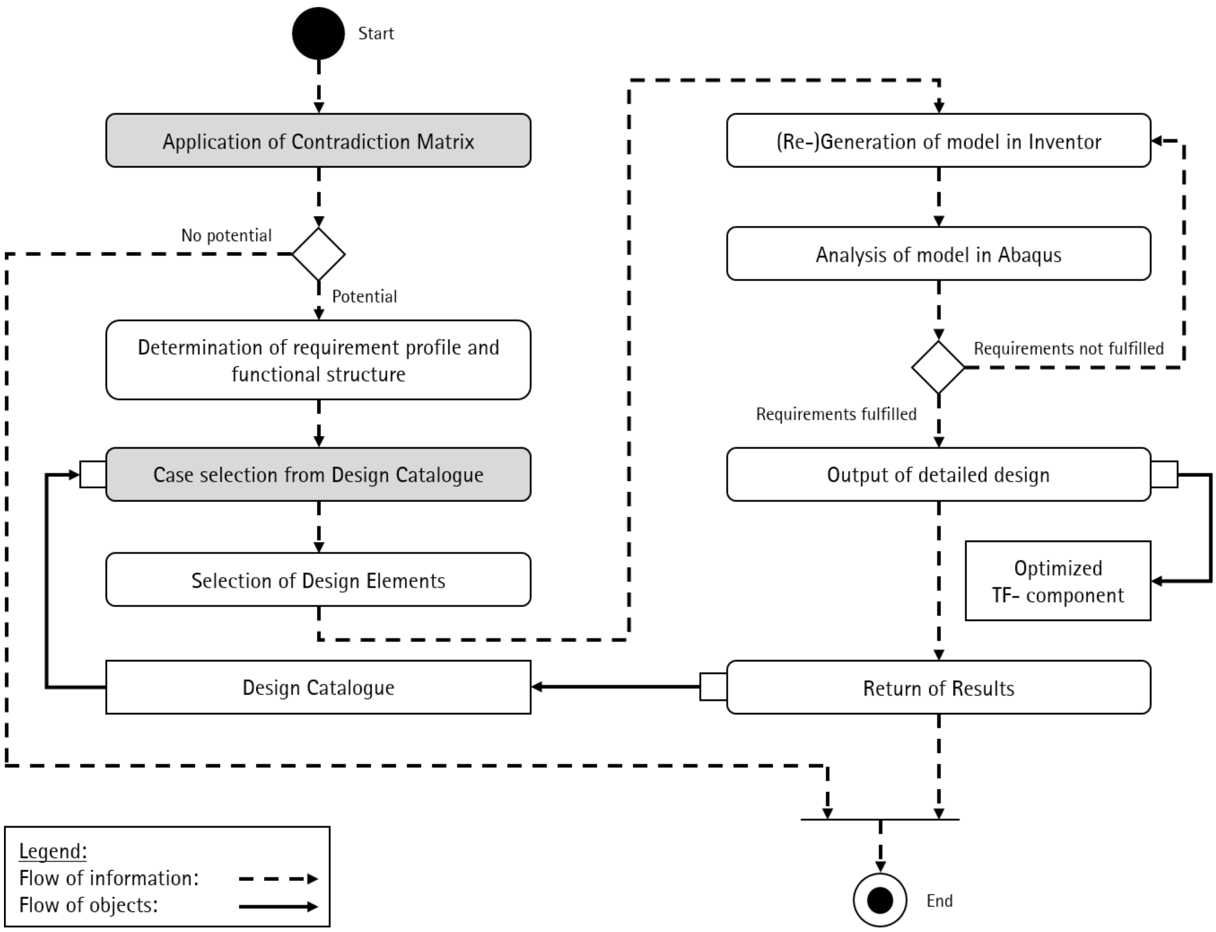


Figure 11: Activity diagram of the computer-aided engineering environment

This draft consists of preconfigured design elements in the sense of the Generative Parametric Modeling and represents the component completely including the joining zone geometry in CAD. Depending on the maturity of the draft, the model can be transferred to an FE system and analyzed. This model also serves as a starting point for the computer-aided optimization, which converges iteratively the properties of the Tailored Forming component to the requirements. The solution, which has been found by the system for the specific task, is recorded together with the corresponding requirements. For this purpose, a second design catalog is set up as knowledge-based system with case-based reasoning. As a result, the development environment is a self-learning system, since the knowledge base is increased with each successfully solved Tailored Forming design task.

5. CONCLUSION

This article describes parts of a computer aided engineering environment for the design of Tailored Forming components. The Tailored Forming Contradiction Matrix serves as a documentation of the Knowledge of Applicability for this manufacturing technology and a starting point for drafting in the CAE environment. The Tailored Forming Design Knowledge, which contains joining zone concepts, design guidelines and specific manufacturing restrictions, is stored in a design catalogue. The draft, which is then provided by this knowledge base, then may be processed to a computer-aided design (CAD) system as starting point for detailed design, simulation and optimization.

Future research targets basically at three major challenges. At first, the library of design elements has to be formulated in order to cover a solution space large enough for a convenient configuration of various Tailored Forming components. The current limitation of drive parts then has to be relaxed where the next step is to include components for chassis development like wheel suspensions etc.

The second challenge is to define adequate optimization strategies. Since the components may be optimized regarding various boundary conditions and parameters, the resulting multi-criteria optimization problem would result in long processing times. Although e.g. genetic algorithms are basically suitable for the task, parameter variation strategies according to the Generative Design Approach have to be researched so that search effort and processing times are reduced.

The third field of research targets at the case base of solved Tailored Forming design tasks. At the current stage, the system is able to identify equal requirement sets. Future development has to enable the processing of similar solutions which calls for the implementation of similarity measures.

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