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INTEGRATION OF STRUCTURAL OPTIMIZATION IN THE ENGINEERING DESIGN PROCESS

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1. Introduction

Today, design engineers are facing several main challenges in a fast moving product development process. Shorter getting product lifecycles and a growing focus on lightweight design force to ensure the product's functionality as early as possible.
To fulfil these requirements several design iterations and prototypes are needed. The application of computer aided design and simulation (CAx-) tools is a common practice to reduce this overhead. Expensive production and testing of prototypes can be avoided by a high level of product maturity in the virtual design stage. Besides, unnecessary reworking can be reduced significantly by a higher probability of error detection during development, as shown in Figure 1 [Vajna 2009]. This enables a successful and economical product development.

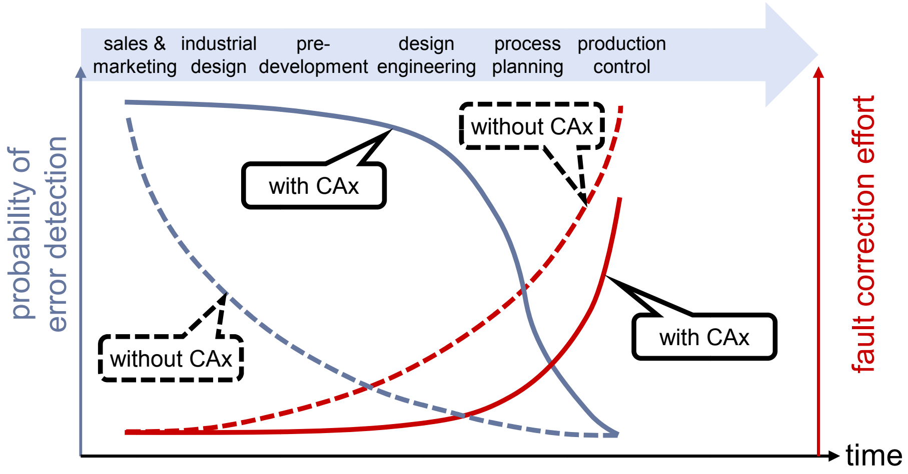

Figure 1. Error detection and fault correction effort during product development according to [Vajna 2009]

The application of CAx software (solid lines) during product development considerably raises the probability of error detection. It also reduces the fault correction effort in contrast to a process without CAx (dotted lines). Thus, if the development costs and the necessary iterations have to be reduced, it is advisable to focus especially on the early product development stages. In other words, the CAx methods and tools allow the design engineer to analyse his design proposals and determine the necessary modifications to improve them iteratively. According to [Walter et al. 2011], the effort for the iterative improvements is mainly defined by the quality of the first design proposal. Concerning its functionality this causes far less effort for following iterations if it is well designed. If lightweight design aspects are additionally taken into account, the product developer should use methods and tools like structural optimization for gaining an optimal initial design [Müller et al. 1999].

Topology optimization enables the product developer to find a lightweight design proposal by computing a discrete geometry of the considered component, while ensuring the product's functionality - especially by meeting the mechanical requirements [Bendsoe and Sigmund 2003]. For example, a common structural optimization task during product development is to maximize stiffness as objective, while minimizing mass for a given set of loads and boundary conditions. The result of the optimization is an optimal material distribution within the given design space, which can then be used as an initial design proposal that already ensures the product's requirements.

For this reason, structural optimization methods and tools should be integrated as a state of the art process during product development and actively be used by design engineers. But this still has not already been established. In practical use the application of structural optimization techniques is typically the task of a simulation engineer and thereby often performed after the important design stages, like embodiment design. On the other hand in the past years there appeared a distinct trend: nearly every established CAD system provides an integrated finite element analysis module to the product developer, e. g. PTC Creo Simulate [Shih 2011], for analysing the design proposals during the design process. Hence the next logical step should be the full integration of structural optimization in the design process. Certainly several problems have to be solved. A survey of [Balázs et al. 2002] analyses the use of optimization techniques in the UK's industry and shows that there are several reservations against these methods and tools (Figure 2).

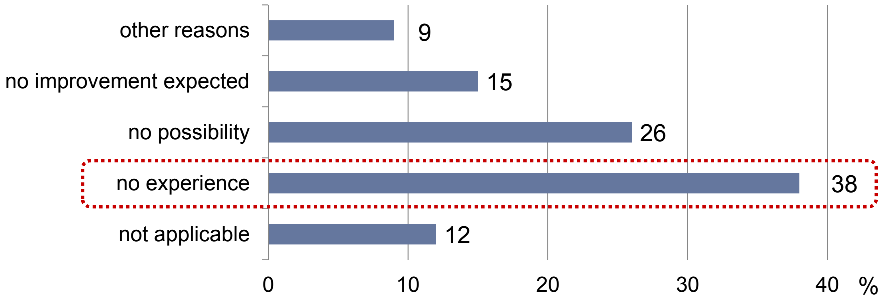

Figure 2. Survey: reasons against the use of optimization according to [Balázs et al. 2002]

Some of the arguments against optimization can be rejected immediately. According to [Schumacher 2012] structural optimization always leads to improvements and is always applicable, assuming that it is used correctly. However, optimization is often applied either too early or too late in the design process and too rare in between during the main time. There is either too little information to gain useful results or the optimization is performed too late, so that anything can be changed hardly. Besides, the most frequently mentioned reason "no experience" shows the necessity of a support for a methodical use of structural optimization. Consequently this paper focuses on the development of an extended design guideline, which supports the design engineer to use structural topology optimization successfully in a methodical way during the engineering design process. First of all, both the state of the art technical integration, and the state of the art methodical integration of structural optimization in the design process will be shown. Based on the state of the art integration the development of an extended integration approach during a design study is presented. Afterwards the new methodology is described in a general manner. The paper closes with a short summary and a future prospect.

2. State of the art

2.1 Technical integration

The common proceeding to perform a topology optimization is divided in three main steps, as shown in Figure 3. During the first step the CAD model of the design space is created, which is subsequently optimized. After performing the optimization the result is reimported as triangulated surface into the

CAD environment. This mesh has to be reconstructed and interpreted by the design engineer as a feature based CAD model that can be adapted to manufacturing and functional conditions.

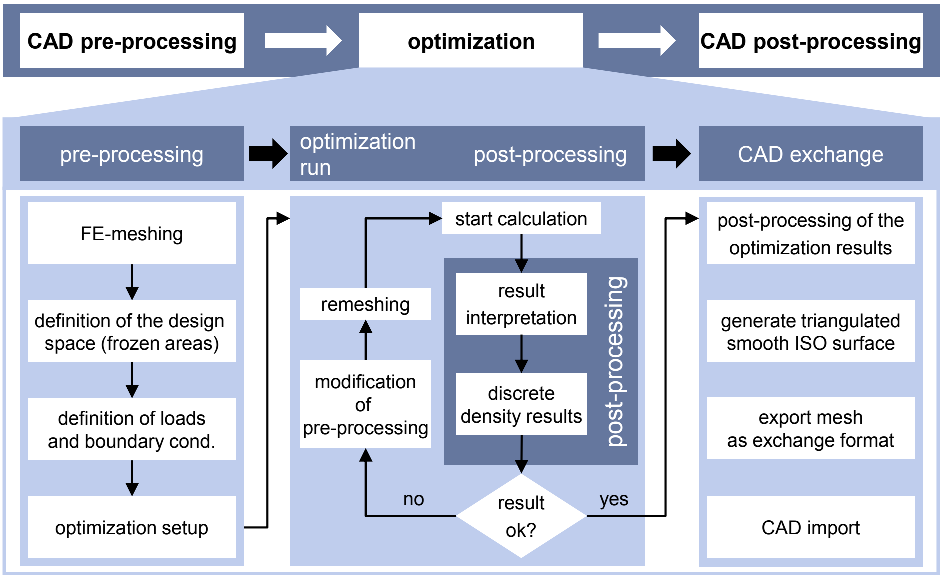

Figure 3. Tasks to perform a topology optimization based on [Hessel 2003]

The optimization itself is divided into three steps: the pre-processing, the calculation step and post-processing. A finite element model of the design space is always the basis for the structural optimization, which is generated during pre-processing by typical finite element tools. After performing the calculation, the topology optimization result needs to be interpreted during post-processing and exported as a smoothed mesh back into the CAD environment.

To support this process the current research for technical integration into the design process deals mainly with a better integration of the optimization pre-and post-processing steps [Hessel 2003]. Especially topics like integration of new manufacturing constraints [Pedersen and Allinger 2006] or the development of new optimization algorithms, e. g. for robust topology optimization under uncertainties [Chen et al. 2010] are in the focus today. Additionally the expansion of topology optimization to other physical fields like optimization of fluid [Aage et al. 2008] or acoustic problems [Yoon et al. 2007] is under present research. Certainly these special problems are typically solved by a simulation engineer and not by the design engineer. But, during the pre-processing steps, the interaction of the design engineer is indispensable because the design space needs to be defined. Additionally the optimization task (what is the aim of the optimization?), loads, boundary and manufacturing conditions need to be defined by the requirements and the conceptual design.

During post-processing the result has to be returned back to the CAD system. This rough design proposal, which is represented by a triangulated surface mesh, has to be interpreted, validated and utilized by the design engineer. At the actual state of the art it remains to decide how this can be solved, due to the lack of special tools.

This topic has to be thoroughly investigated, to allow an automatic or semi-automatic reconstruction of the optimized mesh results as feature-based representation in the CAD environment. There are several interesting approaches like in [Shane Larsen 2009] who shows a framework for converting topology optimization results into parametric CAD models. This is done by gradually removing material from the CAD model of the design space by machining features (extrude, revolve, sweep etc.) at the same position as the optimizer does. But this leads to the problem that cross-sections of the resulting structure concurrently depend on several different features. Consequently an additional adoption of the model to match manufacturing and functional conditions is nearly impossible. There is a missing link between the parameters the design engineer has in mind and the feature parameters.

Perhaps other approaches for a feature-based reconstruction of freeform shape optimization results, like in [Stangl and Wartzack 2013], can be adopted for the reconstruction of topology optimization results, but therefore further investigation is needed.

2.2 Methodical integration

The consistent use of topology optimization, which has previously been the main responsibility of the simulation engineer, depends now forcibly on the design engineer who deals with the design of the product's components. The information flow between different INPUT, e. g. collecting requirements, design and manufacturing knowhow etc. and OUTPUT streams, like usage of CAD and CAE systems, generation of changing announcements, reviews etc. make the design engineer the focal point of a modern product development process [Schumacher 2012]. However, typical calculation methods of the design engineer are largely limited to analytical calculations like sizing and selection or simple (FE) analysis for functional verification.

In practice the interaction between simulation and engineering design can be described as follows: The simulation engineer uses the already completed design draft and checks it by the use of calculation tools, if certain requirements are met or a structural optimization can be performed. The CAD models of the design engineer, where the design process is in the foreground, are often unsuitable for the simulation engineer, so the models need to be prepared for the new purposes [Löffel 1997]. This situation is also similar in the reverse order: the recalculated or optimized components may be difficult to manufacture because the simulation engineer does not have the same manufacturing knowledge and experience like the design engineer. Often multiple iterations between these two sides are necessary. With the use of calculation methods and tools by the design engineer the amount of iterations could be reduced [Steinbrink et al. 1999].

Certainly, not all calculation methods can be used by the design engineer. This statement is supported by the classification of computational methods in the so-called ABC categorization by [Mertens 1995]. The ABC approach divides calculation methods in three categories in terms of their time effort and significance, like shown in Figure 4:

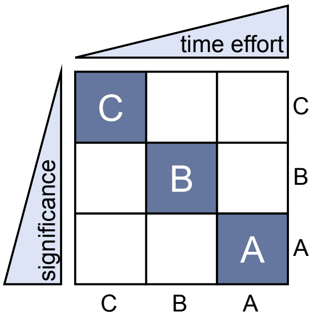

Figure 4. ABC classification according to [Mertens 1995]

- Class C: low significance and time effort; method is controllable by basic knowledge
- Class B: mean significance and time effort; method usable by incorporation
- Class A: high significance and time effort; method is only applicable by specialists

The time effort does not only mean the computation time but also the overhead of creating the simulation models. Therefore, optimal calculation methods would be classified of class A with the effort of class C. This approach would be nearly fulfilled by a methodically supported and computer aided application of elementary topology optimization during the design process. Therefore a structured integration of these tools in the engineering design process is needed.

Until now there are only a few hints in literature that refer specifically to an integrated and continuous application of topology optimization during the engineering design process. [Harzheim 2008] for example tries to describe the conventional product development process and postulates an improved procedure in relation to an early use of topology optimization like shown in Figure 5. According to [Harzheim 2008] the design engineer passes through the main part of the design process in the conventional way and initially creates a detailed CAD model. Subsequently an FE analysis is performed. If required, the design is optimized and revised until the final shape is defined. The improved design process minimizes the iterations between simulation and design by an early integration of topology optimization. This process starts with the generation of the design space, what is by means of CAD a fast and easy process. Next step is the rough design of the component by the use of topology optimization – which can then be finalised and detailed by the design engineer. Optionally an optimization of details, e. g. by the use of shape optimization and a subsequent validation analysis follow until the final design is defined.

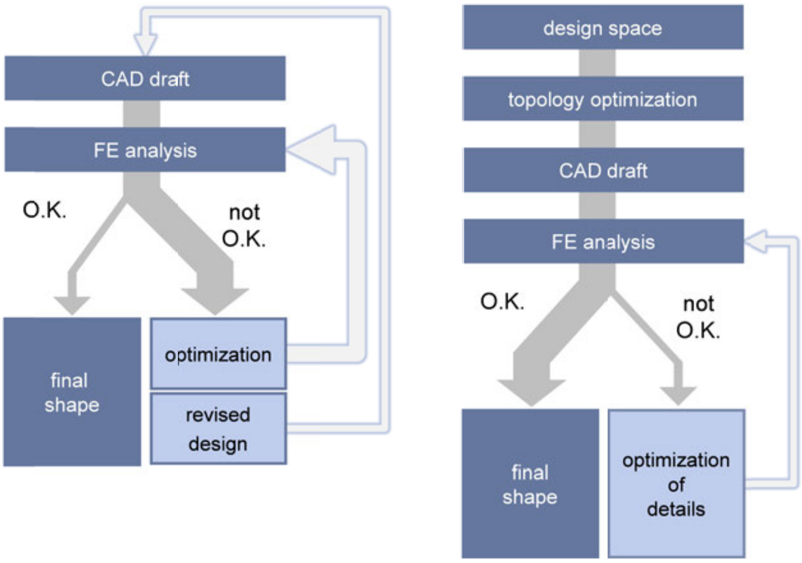

Figure 5. Conventional and improved design process according to [Harzheim 2008]

However, the problem of the HARZHEIM'S improved design process is a certain inaccuracy. Also the reference to detailed and well-established design guidelines, such as the VDI guideline "Systematic approach to the development and design of technical systems and products" [VDI 2221 1993] which is derived from the process model according to [Pahl and Beitz 2013] is missing.

Other sources, like optimization software distributors, speak of the benefits of an early use of structural optimization, for example, in the "design" or "concept" phase. Caution is required when interpreting these terms, which are often used synonymously. Depending on the source of the statement (e. g. simulation engineer, software developer, design engineer etc.) another stage of the design process could be the subject. [Pahl and Beitz 2013] however show that these phases are separated from another, but the transitions between are floating and not always clear. In other words this means that if the simulation engineer speaks of a conceptual design stage this could also be the embodiment design stage referred to the classification of Pahl and Beitz.

According to this guideline the product development process can be divided into four main stages – product planning and clarification of the task, conceptual design, embodiment design and detail design. This well-established approach should be considered when generally integrating structural optimization methods like topology optimization in the engineering design process. This has partially already been done for special purposes, like a tolerance based approach for a simulation based generation of an initial design taking into account geometric deviations and deformations [Walter et al. 2011] or a methodology for generating a robust design proposal by the use of structural topology optimization considering uncertainties [Stangl et al. 2013].

3. Development of the extended design guideline by using a design study

In order to integrate structural topology optimization in the methodological development process and extend simple state of the art methods like the one presented in section 2, a design study was used. The research questions "when optimization work is reasonable?", "which effort necessary for it?" and "which difficulties can occur during the development process?" have to be answered by the design study. Therefore the task to design a gear teeth shaping machine was given to a mechanical engineering master degree student, which was supervised by the authors. The goal was to use a conventional methodical design process to develop a virtual prototype of the machine from scratch. Main requirement to the study was to use structural topology optimization, like described by HARZHEIM'S improved design process, continuously and as early as possible.

The gear teeth shaping machine was chosen as demonstrator to apply the topology optimization not only to a single already known or existing component but rather to use it during a completely new construction of a system. Moreover, the mechanical principle of a gear teeth shaping machine is well-known [Dubbel et al. 2011]. The assembly of the shaping machine consists of a few major components, but offers different elements, such as fixed and moving parts, small and large components, where appropriately different results are expected by the optimization. Thus the limits and possibilities for extending the design guideline can be determined, while the complexity during the study still can be managed. Figure 6 shows an overview of the design study.

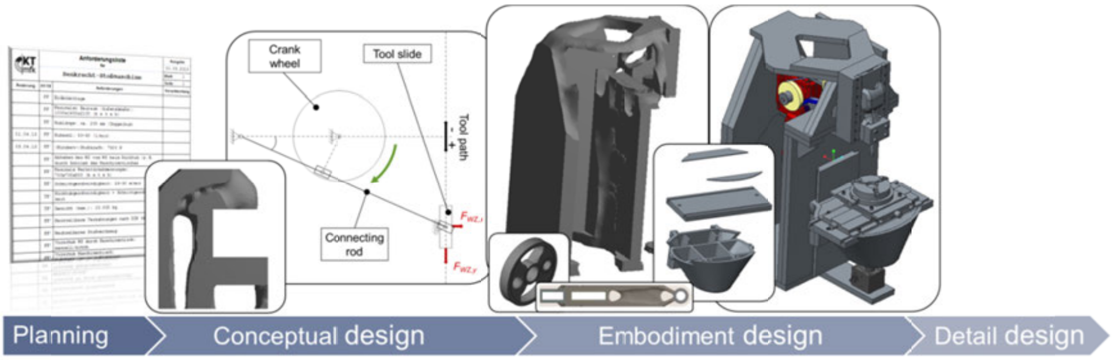

Figure 6. Design study: vertical gear teeth shaping machine

As in a conventional product development process, the first stage of the study puts the clarification of the task and definition of the product's requirements in the foreground. Some important requirements are briefly introduced: the machine should be able to shape splined shaft connections with a nominal diameter of 55 mm. The maximum workspace dimensions are specified to 700 x 700 x 500 mm (width x depth x height). To manufacture different components and component sizes, a movable workpiece clamping on the machine table, which allows the adjustment of the workpiece in x- and y-direction, is required. The movement in the z-direction is performed by the height-adjustable table of the machine. Overall, the stationary machine must not exceed the dimensions of 1000 x 1600 x 2100 mm (width x depth x height). The cutting speed of electrically driven shaping machines is usually between 25 and 30 m/min. Due to the large acceleration forces, the double strokes per minute are limited to a range between 50 and 60 for a tool path of 200 mm. A double stroke consists of the machining stroke and the idle return stroke, which should be faster than the working stroke to increase productivity.

During the second stage, the conceptual design stage, it turned out that the early usage of topology optimization in this stage is very difficult, because of the unavailable kinematic concept of the gear teeth shaping machine. Neither the internal forces nor the possible dimensions of for the design spaces are available. Different principles and kinematics are conceivable for driving the vertical slotting machine, like Figure 7 shows, for sliding crank mechanisms.

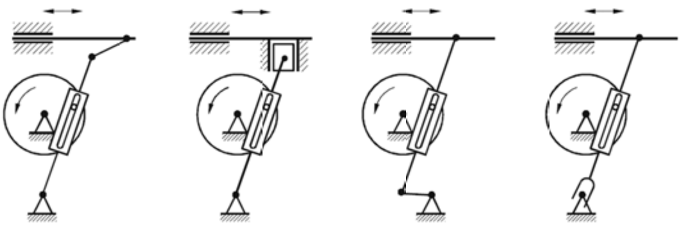

Figure 7. Different layouts of sliding crank mechanims

Several analytical concept calculations and design iterations were needed to search a suitable concept for the kinematics. It was detected that the second stage is mainly the same like in a conventional process before topology optimization can be used. [Löffel 1997] has the opinion too, that computer assistance during the early stages of the development process is difficult. He also says that the first time the use of simulation tools is possible after the search of solution principles. During early phases of the development the creativity of the design engineer is required and not the distinctive usage of simulation. According to that the application of topology optimization for the individual components of the shaping machine is the first time reasonable during early embodiment design. Nevertheless it turned out that an early topology optimization during conceptual design can be used for certain components where the necessary information are given by the requirements list – like for the chassis of the machine, where the maximum dimensions of the design space and the tool load that can easily be determined. But the coarse topology optimization of the chassis during conceptual design (Figure 6) only can help to evaluate the available space for the principle solution.

In the design study the topology optimization mainly was used during the embodiment design of the shaping machine's components – like for the design of the chassis, machine table, crank wheel, connecting rod etc. The design spaces and the CAD draft of the machine are shown in Figure 8.

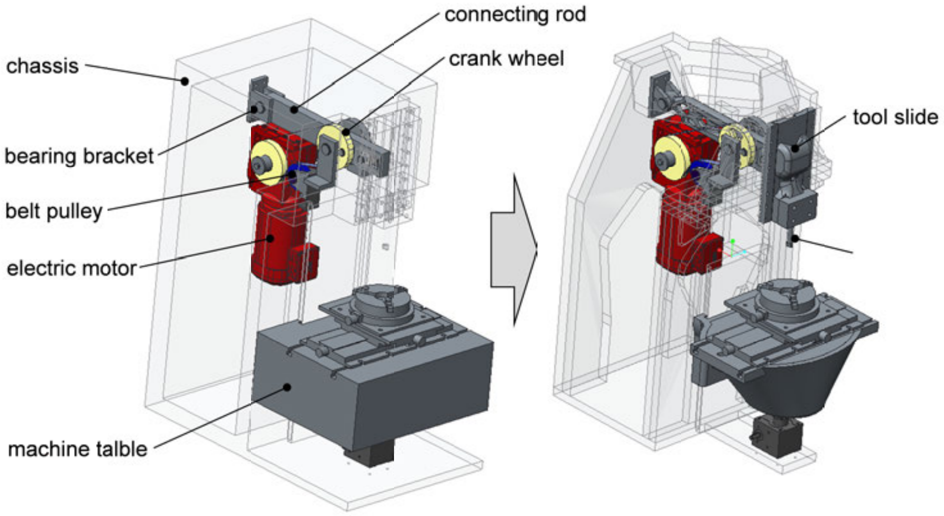

Figure 8. Design spaces and CAD draft of the machine after optimization

The components of the shaping machine were optimized with the aim of maximum rigidity and weight reduction at the same time. The experience during the design study results in the extended design guideline which is presented in the following section.

4. Extended design guideline

This paper provides an extended engineering design guideline based on the already mentioned design methodology of Pahl and Beitz to continuously integrate structural optimization in the product development process. The extended design guideline is shown in Figure 9. During planning stage, clarification of the task and definition of the product's requirements are in the foreground, like within a conventional product development process. Therefore the use of topology optimization would be neither necessary nor possible.

During the conceptual design principle solutions for the system have to be found. An early topology optimization (pre-optimization) can be used to evaluate the available space for the principle solution. The significant use of topology optimization in the conceptual design stage is rarely possible due to the lack of information, but it can already be used for a coarse estimation of the available space within the product for certain parts if enough information are available from the requirements, like the maximum dimensions of the machine and main load. The topology optimization is mainly used during the embodiment design of the product's components. To perform a topology optimization the task needs to be defined and clarified to address the goal of the project. Factors like the optimization objective, available resources and time effort, costs and components to be optimized need to be considered to clarify the task.

Furthermore the requirements of the optimization have to be defined. All constraints like the manufacturing process (the company's available production machines), adjacent structures, boundary conditions of components etc. need to be defined before performing the optimization, as well. Next step during embodiment design is the definition of the design space(s) within the CAD environment according to the principle solution of the product and the previously defined task, requirements and constraints.

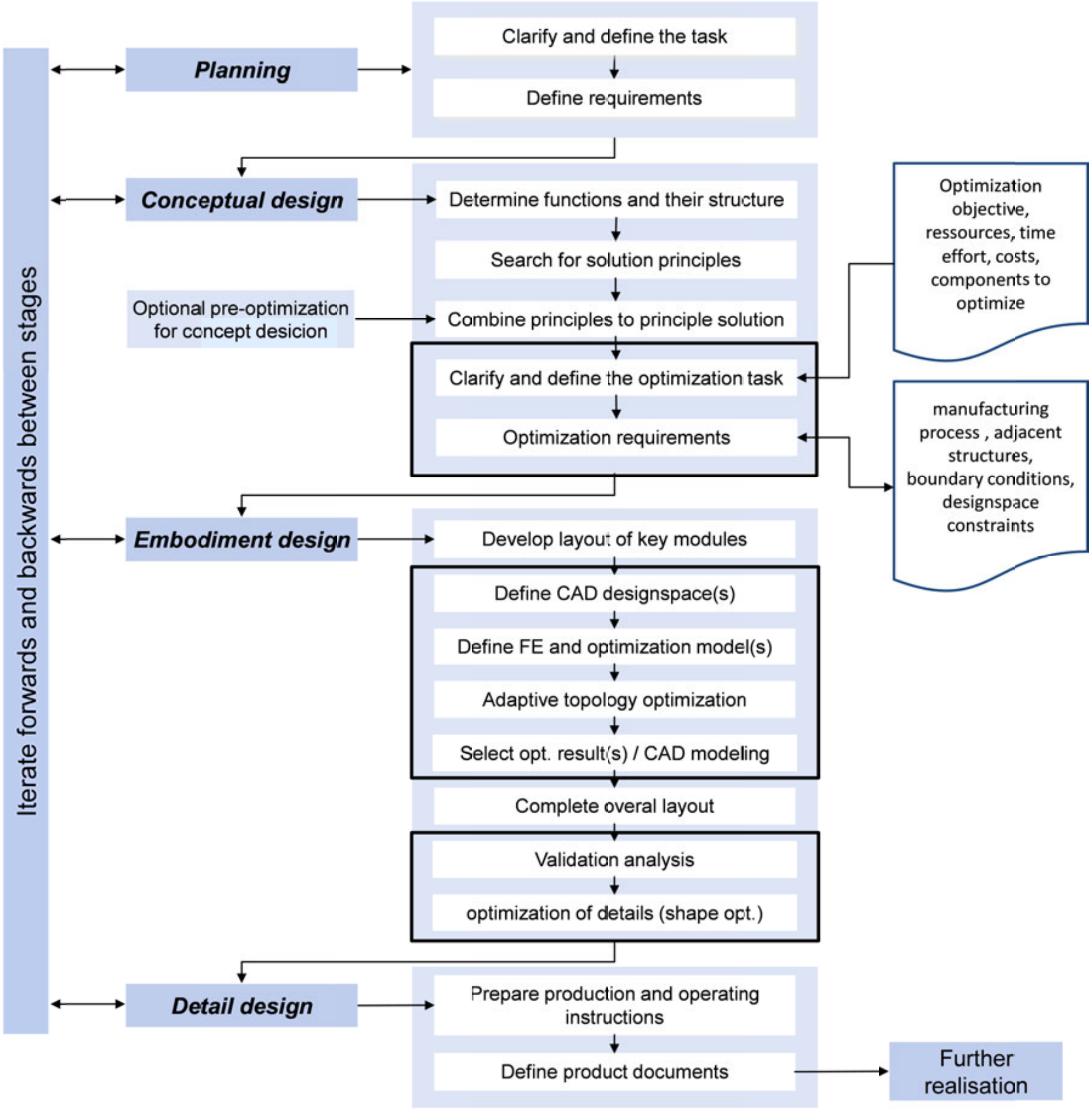

Figure 9. Extended design guideline for a continuous use of structural optimization

By restriction of the design space the formation of an "ideal figure" (optimum) could be inhibited and first errors can arise at this point – so caution is recommended. Following this, a finite element analysis model can be implemented and the optimization model is specified. Therefore the next step there are various ways: in the simplest case, the design engineer accepts the result and follows the next steps. However, at first it is advisable to perform a trial run of the optimization and modify the analysis model and adapt the optimization setup (e. g. manufacturing constraints etc.) until the solution is satisfactory – therefore the term adaptive topology optimization is used in the extended design guideline. Even an adaption of the design space could be necessary. In case of unclearly defined input parameters (e. g. different load cases, optimization algorithms, boundary conditions, manufacturing constraints etc.) multiple solutions (design proposals) are possible and a choice has to be made. The selected design proposal is afterwards reconstructed in the CAD environment taking all manufacturing characteristics into account. At least at this point a suitable manufacturing method has to be selected. Like in a conventional design process the extended process model is also iterative, so if necessary, the CAD design can also be subjected to a further topology optimization. In most cases the design is deviated from the proposal of the optimization due to of manufacturability. Even if the CAD design would be a direct reflection of the design proposal, the result has to be checked against existing material limits, like fatigue strength etc., which is not considered during topology optimization. Therefore after completion of the overall layout of the product a FE analysis is required to validate the CAD design. Depending on the result of this validation, the final design is achieved or the result is subjected to a detailed optimization, e. g. (freeform) shape or parameter optimization. The last stage of the enhanced design process is the definition of the product documents for further realisation. This step follows the conventional design process.

5. Summary and outlook

At the beginning the importance of structural optimization in particular topology optimization has been illustrated for the design process. Reservations about the use of optimization techniques were reproduced on basis of a survey, which shows further need for action. Because the structural optimization can enforce more and more against these reservations due to its advantages, an early and continuous use in product development should be aspired. Finally, according to "do it right the first time" it is desirable to design optimal components from the beginning instead of a time-consuming iterative adaption of the actual design. While the integration of topology optimization is also currently on the technical side constantly evolving, there is little evidence in terms of methodical integration. If optimization is used as early as possible during product development in future, the design engineer will act more and more as a simulation engineer. Therefore the design engineer needs methodological support how to proceed concretely. In order to provide this support, in this paper an extended design guideline was presented which supports the product developer to use structural optimization during the design process in a structured way. The theoretical considerations given by this paper are supported by a design study, in which the entire development process according to the process model of Pahl and Beitz was passed through. Furthermore during the development of the new guideline, it turned out that topology optimization is basically usable during embodiment design. It was also shown that an earlier application within the design stages is difficult due to the lack of information.

By the use of topology optimization during the design study good results can be achieved, but also some limits show up. With the early use of topology optimization for a new design, a problem in relation to evaluation of the benefit occurs: The results cannot directly be compared with a previous component or product, so an estimation of the improvement in concrete is hardly possible. Furthermore, there is the challenge in application of structural optimization techniques that the user needs both a familiarity with design engineering tools like the CAD system, as well as simulation tools and methods, like finite element analysis and structural optimization is required, which is probably rarely encountered in industrial environments. To allow the necessary coupling of the design and the calculation engineer in one person in future computer-aided tools need to be developed that could be classified class A with an effort close to class C according to the mentioned ABC concept [Steinbrink et al. 1999]. This could possibly be reached by specialised knowledge-based tools.

Consequently further development of the technical integration into the CAD-based design process is required and will contribute to the continuous use of structural optimization. Especially the conversion of the topology optimized results in feature-based solid CAD models will help to save time and the acceptance of structural optimization methods. But also available features of the optimization software are not fully developed. For example, the subsequent validation run of an optimization result, e. g. resulting stresses, deformation etc. within the simulation environment doesn't work properly in most cases due to a faulty mesh.

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