INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

SIMULATION BASED GENERATION OF AN INITIAL DESIGN TAKING INTO ACCOUNT GEOMETRIC DEVIATIONS AND DEFORMATIONS

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ABSTRACT
The success of a product's development is essentially affected by its functionality. So the product developer has to ensure the functionality as early as possible. Since this usually can't be achieved with the first design several iterations are needed to modify the design.
The product's functionality depends largely on the interaction of its components and their geometries. So geometric deviations of these components need to be taken into account. These deviations can result e.g. from manufacturing discrepancies or being operation-depending like deformations.
This paper presents an approach which enables the product developer to determine an initial design proposal that fulfils its function. So no time- and money-consuming iterations are needed. Therefore the approach uses methods and tools like tolerance allocation, topology optimization and parameter optimization at an early stage. The tolerance allocation is needed to define the functional requirement of the non-ideal components. The optimization tools are used to create the initial design proposal fulfilling the functional requirement. A case study of a non-ideal scissor-type lift table illustrates the approach.

Keywords: Early functional validation, initial design proposal, non-ideal parts, topology optimization

1 MOTIVATION AND OBJECTIVES
A successful and economical product development goes hand in hand with the ambition to ensure the product's functionality as early as possible during the product development process. However there are usually several iterations needed to achieve a product design that fully fulfils its function.
The functionality of a product is crucially influenced by the interaction of its components [1]. This interaction is influenced by geometrical deviations of the product's components from its nominal geometry. These deviations in dimensions, form and position can result from manufacturing discrepancies. Also operation-depending deviations like deformations of the product's components can occur. These result from the given loads during the products use.
So the product developer has to face the challenge to design a product that's able to fully fulfil its function – despite geometrical deviations of its components. Therefore the product developer has to focus on the design of the components in order to ensure their particular function. Usually this won't be achieved with the product developer's individual first design proposal. Instead, the first design proposal is modified during following iterations until the final design fully fulfils its function.
Therefore a variety of methods and tools (CAx) are available to analyse the already existing first and the enhanced following design proposals concerning their functionality. These also allow an effective determination of the necessary modifications of the product and its components to improve the first design proposal iteratively. Further the effort for the iterative modifications and improvements can be appreciably reduced by the use of these methods and tools. However, the problem still remains, that the effort is mainly defined by the quality of the first design proposal. In other words: A first design proposal that is well designed concerning its functionality causes far less effort for following iterations. This is founded in a lower number of iterations which are needed to ensure the design's functionality. So the product developer should not create an individual and therefore subjective first design proposal but rather use appropriate methods and tools to determine an initial design proposal that already fulfils the functional requirement [2].
This paper presents an approach enabling the product developer to determine an initial design proposal that already fulfils the functional requirement despite geometrical deviations. Consequently the benefit of the approach is that no more time- and money-consuming iterations are needed. Therefore the

common proceeding to achieve a fully functional design needs to be analysed beginning in the embodiment design stage with the first design proposal and ending with the final geometrical description that fulfils the functional requirement. Based on a modification of the common proceeding the new approach can be derived. This approach (detailed in chapter 3) enables the product developer to determine the required, fully functional initial design proposal at an early stage by means of appropriate methods and tools as tolerance allocation, topology optimization and parameter optimization. Afterwards the developed approach will be used to determine a fully functional first design of a deviation-afflicted scissor arm which is a component of a scissor-type lift table. The closing chapter summarizes the paper and addresses future prospects.

2 STATE OF THE ART

The product development process can be classified into four stages (product planning and clarification of the task, conceptual design, embodiment design and detail design) [3]. The first design proposal will be generated at the beginning of the embodiment design taking into account the requirements defined in the first stage and the specified concept in the second stage of the product development process. Usually the first design proposal won't be the final design which fulfils all given requirements. This results in the necessity of analysing the first design proposal and to set up following optimizations in order to improve the design. Finally an additional analysis reveals the achieved improvements and enables the product developer to evaluate the modified design.
This paper considers products needing to fulfil functional requirements. These are affected by geometrical deviations due to manufacturing discrepancies which are limited by tolerances. Also deformations of the product's components are taken into account resulting from the given loads during the products use. Figure 1 shows the common procedure of analysing the design in terms of fulfilling the functional requirement using a structural mechanical analysis and a tolerance analysis.

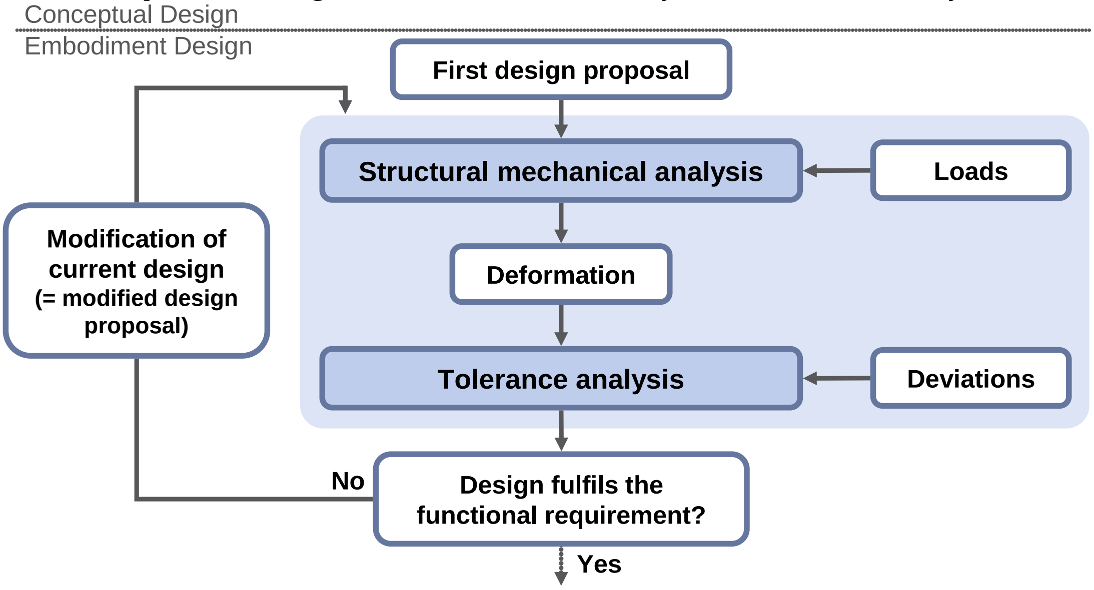

Figure 1. Common procedure analysing the functionality of the first design proposal

The tolerance analysis enables the designer to determine the impact of possible geometric deviations of the components on the product's functionality. The tolerance analysis procedure can be separated into three steps beginning with the formulation of the mathematical relation between the toleranced parameters and the functional key characteristic. According to [4] the functional key characteristic is a parameter of a product, sub-assembly, part, process or resource that significantly impacts the final cost, performance, or safety of a product (e.g. a dimension of an assembly like the gap between two parts of a car body). There are multiple ways to determine this mathematical relation based on different forms of representing the tolerances. An overview is given in [5] and [6]. The following step enfolds the analysis itself. Based on the mathematical relation the variation of the functional key characteristic resulting from varying parameters of the product's components will be determined. Depending on the given information about the product and the distributions of the varying parameters either an arithmetical or a statistical tolerance method can be performed. While the arithmetical

methods determine the functional key characteristic only for the maximum and minimum values of the parameters (worst-cases) the statistical methods are taking into account the parameter's entire variation [7]. Finally the tolerance analysis closes with an appropriate representation and interpretation of the results.
The finite-element-analysis is one of the most important numerical methods to solve mechanical problems. By means of these tools it is possible to set up a structural mechanical analysis in order to determine the deformations of components based on the first design proposal. With both geometric deviations resulting from manufacturing discrepancies and the deformations during the products use the needed inputs for a tolerance analysis are available and the first design proposal can be analysed in terms of fulfilling the given functional requirement.

3 WORK METHODOLOGY

The common proceeding of analysing the product design has to face some major problems justifying the effort to improve the current design-validation process:

- In general the product developer is more often faced with the problem of tolerance allocation instead of tolerance analysis. [8]
- The product developer's individuality results usually in a subjective first design proposal not necessarily considering upcoming functional problems.
- The fulfilment of the functional requirement is checked for the first time when the design proposal is completely created.

These problems lead to time- and money-consuming iterations to enhance the current design proposal and to a product development process suffering from a lower efficiency. So obviously the main question is how to avoid or reduce these problems.
In this paper an approach will be presented that faces these problems by enabling the product developer to determine an initial design proposal which already fulfils the functional requirement. The quintessence is that the fulfilment of the functional requirement will no longer be seen as a question that will be answered at the end of the analysis. It will be considered as an essential and mandatory claim for the product that has to be fulfilled at any time.
So the common procedure (figure 1) can be turned upside down – starting with the claim "Design has to fulfil the functional requirement" and ending with a fully functional initial design proposal. The steps analysing the design (structural mechanical analysis and tolerance analysis) have to be replaced by its inversions. Formally the inversion of an analysis is the synthesis [9]. In this case the structural mechanical analysis and the tolerance analysis can be replaced by the topology optimization and the tolerance allocation. Figure 2 shows the approach.

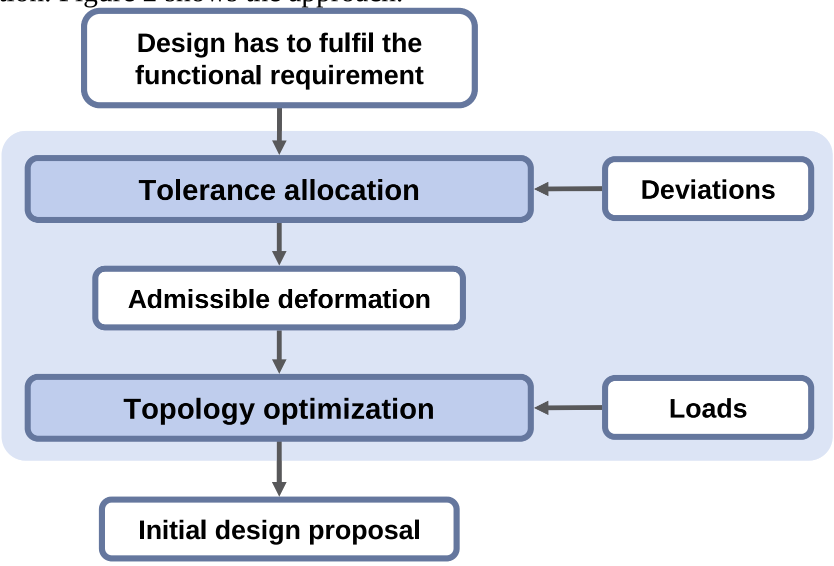

Figure 2. Approach to determine the initial design proposal which fulfils the functional requirement despite geometrical deviations and deformations

Based on a product concept that is developed during the conceptual design-stage the first synthesis is the tolerance allocation. The tolerance allocation is the inversion of the tolerance analysis.

The tolerance analysis (as detailed in chapter 2) is used to determine the variation of the functional key characteristic of an assembly based on the given deviations and deformations of the components. Consequently the tolerance allocation enables the product developer to distribute the tolerated variation of the functional key characteristic of an assembly among the variations of the components according to an allocation scheme [9, 10, 11]. Figure 3 clarifies the difference between tolerance analysis and tolerance allocation of products whose components are affected by geometrical deviations and deformations.

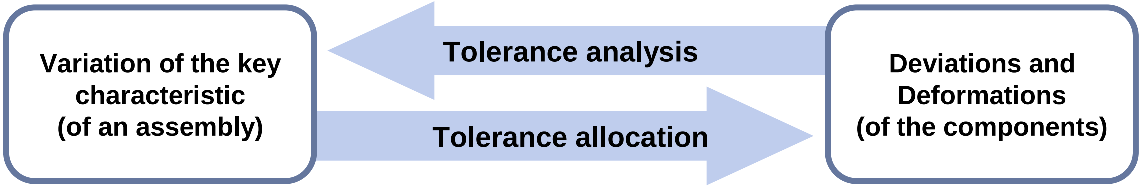

Figure 3. Tolerance analysis and tolerance allocation

Analogue to the tolerance analysis the tolerance allocation needs a mathematical equation describing the relation between the component's deviations and deformations and the functional key characteristic. Both, deviations and deformations are unknown variables of the equation while the specification limits of the key characteristic are defined by the functional requirement. To solve this equation either the deviations or the deformations have to be defined. According to the approach it is necessary to determine the admissible deformation of the components. So the component's deviations must be known. At an early stage there are two possibilities to define proper tolerances which are limiting the unknown deviations of the components:

- Tolerances are chosen based on expertise or experience (from previous projects, lessons learned etc.)
- Tolerances are defined by the general tolerances according to ISO 2768-1

The admissible deformation of the product's components – as the result of the previous tolerance allocation – is needed as a constraint for the following topology optimization.

As Figure 4 shows the topology optimization is an inversion of the structural mechanical analysis which is performed in the common procedure. Both, the structural mechanical analysis and the topology optimization are based on the finite-element-method. The structural mechanical analysis is used to determine the deformation of a component based on the component's geometry. However the topology optimization enables the product developer to determine a discrete geometry of the considered component that resists the given loads [12].

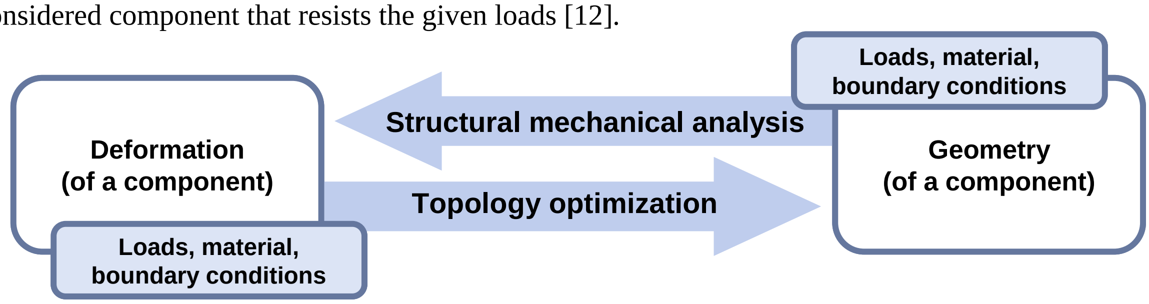

Figure 4. Structural mechanical analysis and topology optimization

This can be achieved by determining the optimum against the backdrop of two diverging requirements – the so-called "objective" and the "design constraint". In this case these two requirements are:

- Minimize the mass of the component (= objective), while
- The component's deformation doesn't exceed the admissible maximum (= design constraint)

Beside the admissible deformation the component's loads during the product's use, the material, the existing boundary conditions and the design space have to be defined.

The determined optimum structural shape is the initial design proposal fulfilling the functional requirement. Usually this structural shape is very difficult to produce due to its complex shape. In order to enhance this initial design proposal the product developer has to transfer it into a CAD model which can be modified. Since these modifications affect the fulfilling of the functional requirement a following parameter optimization ensures the functionality of the design [13].

With a higher complexity of the considered component the modification of the initial design proposal can be effectively enhanced by taking into account manufacturing restrictions (e.g. minimum wall thickness) during the topology optimization. Also the use of reverse engineering to transfer the initial design proposal into a CAD model can be helpful for the product developer.

4 CASE STUDY

In order to demonstrate the approach in practical use a case study has been performed. After the introduction of the demonstrator the functional key characteristic (and the functional requirement) and its impacts (geometrical deviations and deformations of components) are defined.
The first step of the approach – the tolerance allocation – is divided into two steps. The mathematical relation between the functional key characteristic and the geometrical deviations and deformations has to be determined. Therefore also the kinematics of the system must be taken into account. The second step includes the calculation of the admissible deformation of the deformable components based on a proper allocation scheme. The following topology optimization and parameter optimization result in an initial design proposal that fulfils the requirements concerning function and production.

4.1 Demonstrator: Scissor-type lift table

Mechanisms and their kinematical behaviour often act sensitive to (the variation of) non-ideal components due to manufacturing deviations and deformations. In this case study the demonstrator is a scissor-type lift table used e.g. to lift heavy parts during an assembly. The lift consists of three scissor arms: Two similar outer arms with the length l_1 and in between an inner arm with the length l_2. The lengths are the distances between the upper and the lower revolute joints of the scissor arms (A-B, C-D). Figure 5 shows the concept sketch of the lift table that can be considered as a 2-dimensional problem due to a symmetric design concerning the depth.

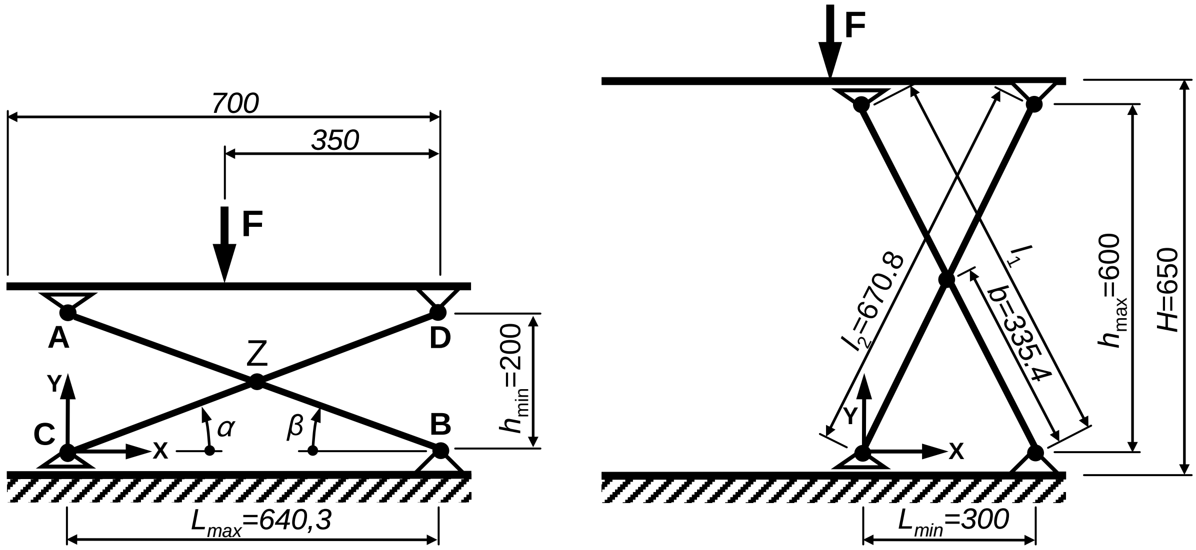

Figure 5. Scissor-type lift table in its two end positions (minimum and maximum height)

While the inner scissor arm (length l_2) and the upper plate are considered as ideal and rigid (no deviations and deformations) the outer arms are non-ideal (deviation of the distance between the revolute joints l_1 and elastic deformation of the arms). As shown in figure 6 this results in a height difference Δh between the upper revolute joints of the scissor arms (joints A, D) causing an inclination of the upper plate of the lift table. L is the horizontal distance between the upper joints of the scissor arms. To avoid the lifted part to slip away at any height of the lift table the inclination of the upper plate has to be limited. This limitation is the functional requirement of the lift while the angle γ is the functional key characteristic. In this case the maximum inclination angle should be $\gamma_{max}=0.5°$.

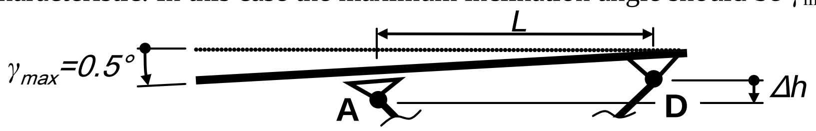

Figure 6. Functional Requirement: Limitation of the inclination angle γ_{max}

The challenge is to determine an initial design proposal of the outer scissor arms (length l_1) which fulfils the functional requirement despite a deviation of the length l_1 and the elastic deformation due to the loads the table has to lift.

4.2 Tolerance allocation

The admissible deformation of the outer scissor arm has to be determined in order to perform a topology optimization. According to the approach (detailed in figure 2) this can be achieved by means of a tolerance allocation starting with the mathematical relation between the functional key characteristic (inclination angle) and the geometric parameters (both ideal and non-ideal) of the components of the scissor-type lift table.

Mathematical relation

According to figure 6 the inclination angle γ of the upper plate results from a height difference Δh between the upper joints of the scissor arms:

$$\gamma = \arctan\left(\frac{\Delta h}{L}\right) \tag{1}$$

The mathematical relation between the height difference Δh and the ideal and non-ideal geometric parameters of the components can be determined using trigonometric functions since the kinematics of the table is still manageable. Towards more complex systems (complex kinematics, more components, more deviations etc.) matrix transformations of coordinate systems are a proper way to determine the mathematical relation.

In the case of the lift table the relation can be determined by transforming local coordinate systems which are fixed in the scissor arms joints A and D. The positions of the upper joints A and D can be described in a global coordinate system by multiplying the associated homogeneous (4x4) transformation matrices. The matrices describe the transformation of the local coordinate system into the global coordinate system (X-Y) taking into account geometrical parameters of the components. This proceeding is used to represent the kinematics of bodies in multibody dynamics [9, 14] and has been modified to enable the representation of geometric deviations and deformations [15, 16, 17]. Concerning the scissor-type lift table it is necessary to determine the relations describing the Y-coordinates of the two upper joints A and D in the global coordinate system taking into account the deviation of l_1 and the deformation V_Y of the outer scissor arms. Figure 7 shows the Y-coordinates of the two joints A (height h_1) and D (height h_2). V_Y is the deformation of the outer scissor arms along the Y-direction of the global coordinate system X-Y.

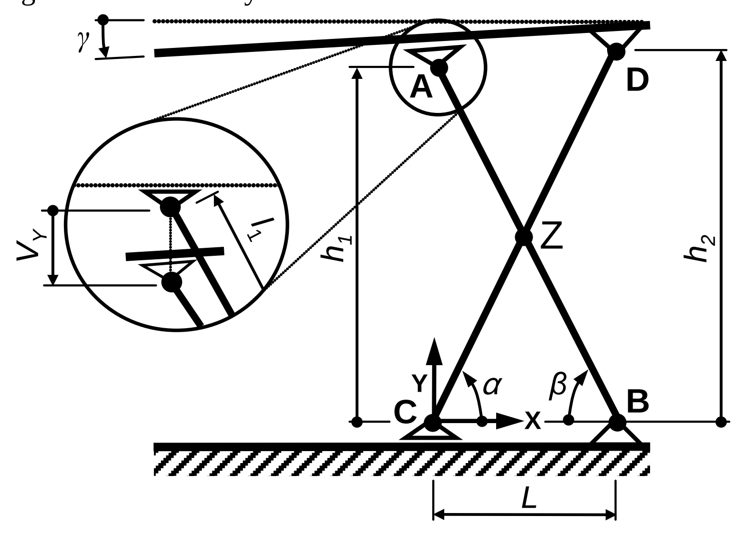

Figure 7. Heights (h_1, h_2) of the joints A and D due to deviation of l_1 and deformation V_Y

After determining the height difference Δh the mathematical relation between the inclination angle (functional key characteristic) and the geometric parameters can be formulated. The angles α and β depend on the current position of the lift table and can be determined using the given parameter l_1, l_2, b and L:

$$\gamma = \arctan\left(\frac{l_2 \cdot \sin(\alpha) - \left(l_1 \cdot \sin(\beta) - V_Y\right)}{L}\right) \tag{2}$$

with:

$$\alpha = \arccos\left(\frac{l_2^{\,2} + 4 \cdot L^2 - 4 \cdot b^2}{4 \cdot L \cdot l_2}\right) \tag{3}$$

$$\beta = \arcsin\left(\frac{l_2}{2 \cdot b} \cdot \sin(\alpha)\right) \tag{4}$$

Kinematics

According to equation (2) the functional key characteristic depends beside on the geometrical parameters also on the current position of the system represented by the parameter L and the angles α and β. To ensure that the lifted part doesn't slip away at any time the motion of the lift table needs to be taken into account. Since the topology optimization only allows static analysis [2] the critical position (worst-case) of the scissor-type lift table concerning the inclination has to be defined. In this case it is sufficient to consider the two end positions.

As the inclination angle γ is directly proportional to the angle β, the critical end position of the table concerning the deviation of the length l_1 is the upper end position. In case of the deformation a distinction of the two end positions is needed. Figure 8 shows both positions with its load F and the support reactions F_{low} and F_{up} that cause the deformation of the outer scissor arms.

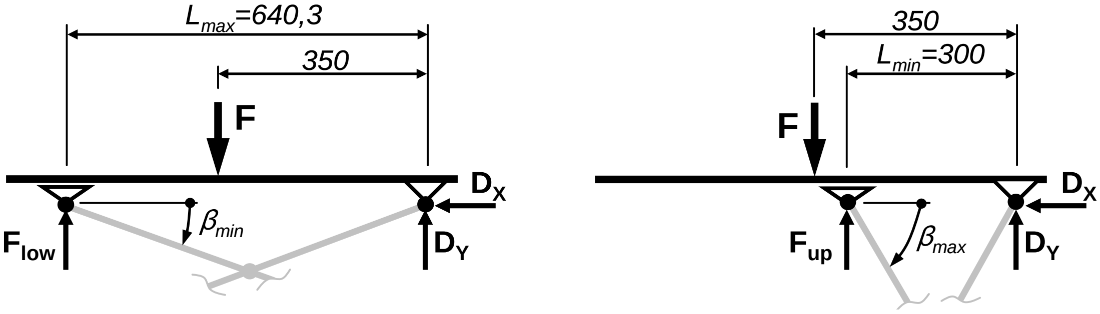

Figure 8. Load and support reactions of the lower (left) and upper (right) end positions

While the force F_{up} (upper end position) is much higher than F_{low} (lower end position) only components of these forces – rated by the factor sin(β) – result in a bending deformation. The ratio R compares these two constellations.

$$R = \frac{F_{up} \cdot \sin(\beta_{\max})}{F_{low} \cdot \sin(\beta_{\min})} \approx 1 \tag{5}$$

The calculation of the admissible deformation has to be performed for the lift table in its upper end position which is the worst-case constellation concerning the functional requirement. This is caused by the higher impact of the deviation l_1 and the parameter L on the height difference Δh. The impact of the deformation on the inclination angle is equal at both end positions. All in all this leads to a lower admissible deformation of the outer arms in the upper end position.

Calculation of the admissible deformation

The admissible deformation is the smallest deformation that can occur in the previously defined worst-case constellation (upper end position) but still fulfils the functional requirement.

Both the deviation of the length l_1 and the deformation V_Y of the outer scissor arms are unknown variables of the mathematical relation describing the functional key characteristic. To determine the admissible deformation of the outer scissor arms for the worst-case all geometric parameters of the system have to be defined. Furthermore the deviation of l_1 needs to be defined. As mentioned in chapter 3 the deviation can be defined using expertise or general tolerances. In this case the tolerance class "medium" within the general tolerances (ISO 2768) results in l_1 = 670.8 ± 0.8 mm. The smallest admissible deformation occurs at the lower specification limit of the length l_1 = 670.0 mm. Table 1 gives an overview of the needed values of the parameters to determine the admissible deformation.

Table 1.Values of the parameters to solve the mathematical equation

l_1	l_2	α_{max}	β_{max}	L_{min}	γ_{max}	F
670.0 mm	670.8 mm	63.43 °	63.43 °	300 mm	0.5 °	3000 N

With the given values of the parameters the mathematical relation can be transformed to determine the remaining smallest admissible deformation of the outer scissor arms V_Y (which is in this case V_Y = 1.90 mm).

Since the case study presented in this paper only considers one component of the demonstrator as deformable the smallest admissible deformation can definitely be determined by solving equation (2). With an increasing number of deformable components an allocation scheme is needed which defines how the total scope of admissible deformation will be allocated among the components. Similar allocation schemes are used for the allocation of tolerances taking into account e.g. the relations between tolerances and costs (least-cost tolerance allocation) [10, 18].

4.3 Topology optimization

According to the approach to determine an initial design proposal of the outer scissor arms a topology optimization is performed. As mentioned in chapter 3 there are several information needed to set up the optimization.

The force F_{up} that lasts on the scissor arms has already been determined in the previous step during the consideration of the table's kinematical behaviour. With two outer scissor arms sharing the given load in equal parts each scissor arm is loaded with the half of F_{up}. Since the scissor arms can be easily cut out of a flat plate (e.g. using laser cutting) a simplified FE-model uses shell elements with a thickness of 10 mm to represent the design space with its dimensions 730 mm x 45 mm. The distances between the joints are defined by b and l_1. Therefore the nominal value of l_1 can be used since the deviations of l_1 have a negligible influence on the arm's structural shape. Finally with the definition of the arm's material (steel) all needed information are given (see table 2). The determined initial design proposal of the outer scissor arms is shown in figure 9.

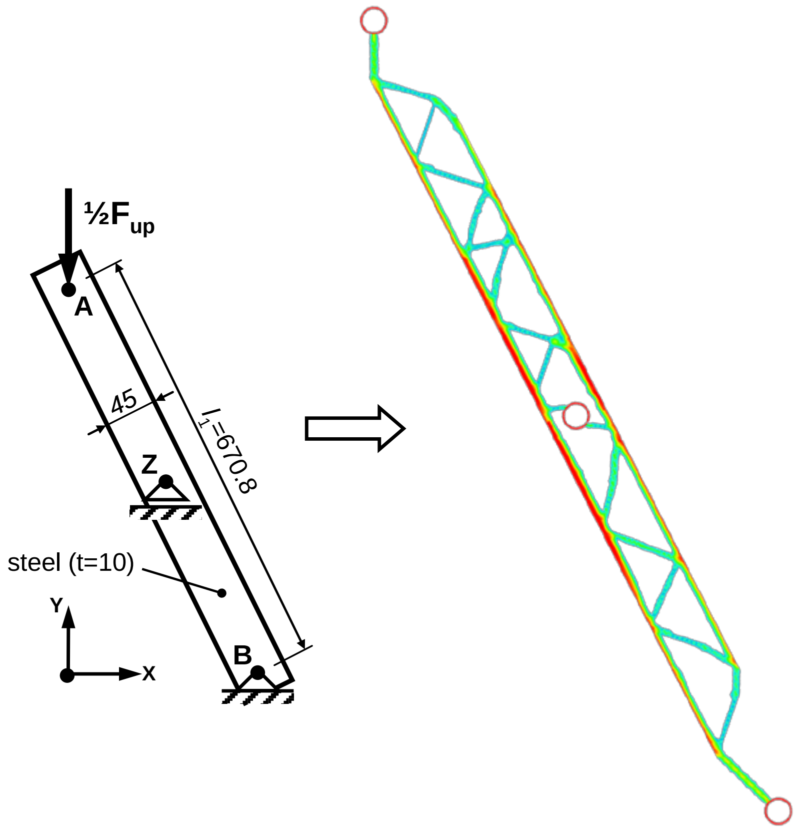

Figure 9. Initial design proposal (structural shape resulting from the topology optimization)

Table 2. Values of the parameters needed to set up the topology optimization

F_{up}	Material	Density	Young's modulus	Poission's ratio	Design space
3500 N	steel	7.85 g/cm³	210 GPa	0.3	730 x 45 x 10 mm

4.4 Parameter optimization

The determined initial design proposal is the structural shape optimum of the outer scissor arms fulfilling the functional requirement. However it's not necessarily a design that also allows an effective production. In order to achieve a design that fulfils the functional requirement and that's also advantageous concerning its production a parameter optimization follows the performed topology optimization to enhance the initial design proposal.

Therefore the essential structural shape (load paths) of the initial design proposal has to be transferred into a CAD model of the scissor arm. In this case the use of reverse engineering isn't needed since the structure of the arms is quite simple. In order to achieve a design that is both fully functional and easy to produce the CAD model undergoes some modifications (e.g. constant thickness of the arm's inner structure).

These modifications of the initial design proposal cause that the arm's deformation is either lower or higher than the admissible deformation. So the functionality of the arm and the lift table can't be ensured. The performed parameter optimization enables the product developer to compensate the impact of the modifications. In this case the parameter is the thickness of the plate the arms are cut out. The aim of the parameter optimization is to exploit the scope of deformation that is limited by the admissible deformation $V_Y = 1.90$ mm. So the maximum deformation of the arm has to be nearly equal to the admissible deformation. Also parameters like the thickness of the inner structural reinforcements can be taken into account. Figure 10 shows the optimized design proposal with an optimized thickness of $t_{op} = 5.2$ mm and a mass of $m_{arm} = 0.545$ kg.

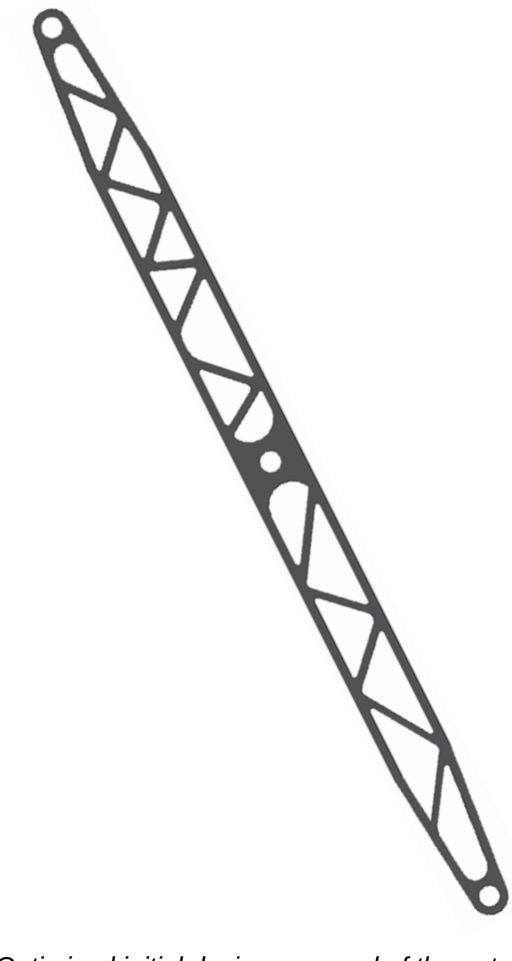

Figure 10. Optimized initial design proposal of the outer scissor arms

This optimized initial design of the outer scissor arms is the final result of the case study using the presented approach. It is both fully functional and advantageous concerning its production and especially has been determined without any time- and money-consuming iterations.

5 SUMMARY AND OUTLOOK

In this paper a new approach was presented which enables the product developer to determine a design proposal of a non-ideal component at an early stage. The benefit of the approach is that no money- and time-consuming iterations are needed since the initial design is already fulfilling the functional requirement despite the component's geometrical deviations. In this case deviations which result from manufacturing discrepancies and deformations of a component were taken into account.

The common procedure asks the product developer to create a design proposal at first. The following analyses of this design proposal point out whether the functional requirement is fulfilled or not. If not, iterations are needed to modify the first design proposal and to achieve a functional component. The presented approach doesn't ask for a design proposal at first since its functionality isn't ensured. Instead, the fulfilling of the functional requirement is considered as an essential and mandatory claim for the product that has to be fulfilled at any time. The first step has to be a tolerance allocation which allows the determination of the admissible deformation of the considered component. A following topology optimization uses the admissible deformation as a design constraint to determine the optimum structural shape of the component that fulfils the functional requirement. In order to achieve a design that also can be efficiently produced a parameter optimization follows the performed topology optimization to improve the initial design proposal. To illustrate the approach a case study of a scissor-type lift table has been performed. The non-ideal components were the table's outer scissor arms (length deviation and deformation).

Basically the approach works for quite simple systems (like the scissor-type lift table) as well as for more complex systems. However the increasing complexity of the systems places high demands on both the product developer and the used methods and tools. So a further direction in research is to improve the presented approach towards more complex technical systems e.g. taking into account more kinds of deviations. Aside of the dimensional variation and the structural effects also thermal effects and wear effects are affecting the functionality. Figure 11 shows several kinds of effects affecting the functionality.

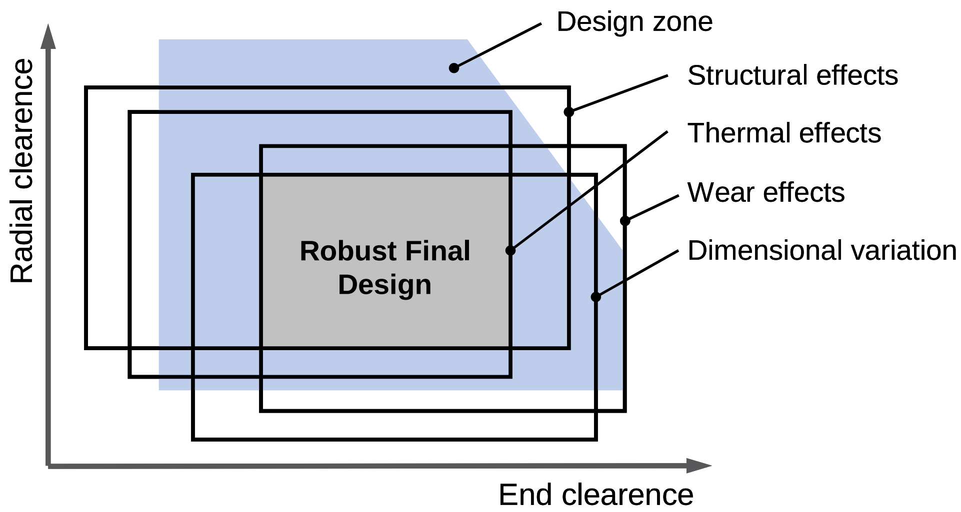

Figure 11. Effects that are affecting the functionality of a product [19]

Usually complex systems have more than one deformable component. So to determine each component's admissible deformation a proper allocation scheme is needed. Similar schemes are used for tolerance allocation taking into account e.g. the relation between tolerances and costs.

Furthermore the impact of the deviations on the results of the topology optimization and the parameter optimization can't always be neglected since these deviations are not always negligibly small compared to the component's dimensions. This leads to the need of statistical topology and parameter optimizations.

In addition to this, a pure static view of dynamic systems falsifies the results since the impact of e.g. moving masses on forces isn't considered. This also causes that the critical position of the system can't be as easily defined as shown the case study. Consequently the use of a multibody dynamics and motion analysis tool is needed to take the system's motion behaviour into account.

ACKNOWLEDGEMENT

The authors thank the German Research Foundation (DFG) for supporting the research project ME1029/16-1 "Functional product validation and optimization of technical systems in motion as a part of product lifecycle oriented tolerance management".

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