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Control of Uncertainties within an Interdisciplinary Design Approach of a Robust High Heel

Within this paper the combination of several methods, developed and used in Collaborative Research Center (CRC) 805 – "Control of Uncertainties in Load Carrying Systems in Mechanical Engineering" of the DFG (German Research Foundation), is used to demonstrate the development of a load carrying system under uncertainty. The development starts with the identification of relevant uncertainties, followed by a conceptual design and a mathematical robust optimization approach. The optimized structure is used for the layout of a 3D-CAD-model which is used to print a real rapid-prototyping-model. Throughout the whole design process uncertainties are considered. To demonstrate the symbiosis of these methods an example is chosen. Usually, CRC 805 deals with load carrying systems in mechanical engineering. To let this topic become more vivid and to show that the methods can be transferred to other fields, the design of a robust high heel is taken as an example. At the end of the work three high heels are developed and evaluated regarding their robustness against uncertainties.
Keywords: *uncertainty analysis, robust design, robust optimization, visualization, high heel*

Introduction

In load-carrying structures uncertainty is caused by several influencing factors like unknown usage, variation in material properties, deviation in production processes, unknown information, etc. Those uncertainties need to be considered in the development process of a product. Controlling uncertainties in load-carrying structures has furthermore the potential of minimizing safety factors and avoiding over-sizing. This leads to economic advantages, saved resources and the extension of application areas. Therefore uncertainties are identified, described and evaluated in a process model to control them by various methods and technologies. To control uncertainties in load carrying systems, such as chassis, bicycles or truck-mounted cranes is the aim of Collaborative Research Center (CRC) 805 – "Controlling uncertainty in load-carrying structures of mechanical engineering". Within CRC 805 several research areas are involved to analyze and control uncertainties in all phases of the design process. Uncertainty occurs when process properties of a system cannot be determined (Engelhardt et al., 2009). Uncertainties mainly refer to deviations of properties, which occur during the product life cycle's processes. To identify uncertainties it is important to consider the whole product's life cycle. Within this work, products that are generally insensitive against uncertainties are called robust products. To achieve a robust product several methods can be applied. The systematic exertion of these methods is regarded within this paper and it describes the interdisciplinary collaboration of mechanical engineers and mathematicians. To demonstrate the combination and interaction of the methods, a concrete example is chosen. The task is to develop a high heel which is unsusceptible against arising uncertainties in the production and the usage of the product. Additionally, the methods developed in science could be connected and verified in a practical project. The design of the high heel and the linking between the models and methods will be displayed with intermediary results of each design phase. The work starts with the analysis of the usage processes of a high heel and identification of relevant uncertainties, e.g. the angle of the applied load, unknown user-weight or the knuckle angle. The entity of the identified uncertainties is the basis for the conceptual design and first simple sketches of the high heel. Abstracting into a truss topology design model allows the usage of a mathematical robust optimization approach. The optimized structure is used for the layout of a 3D-CAD-model. The work finishes with realistic rapid-prototyping-models of the designed high heels and an evaluation of three different high heels regarding their robustness compared to a standard high heel. At the end of this paper one high heel is chosen which meets the requirements best regarding uncertainties.

This idea was part of a competition, called "Achilles High Heel" for female and male students guided by the Gender equality team of CRC 805, which was motivated by gender equality issues.

Nomenclature

$A(v)$ = *stiffness matrix*
c_f = *compliance for given load f*
$f_s \in \mathbb{R}^n$ = *loading scenarios*
U_f = *uncertainty set for loadings*
U^Δ = *polyhedral uncertainty set*
U° = *ellipsoidal uncertainty set*
$v \in \mathbb{R}^m$ = *bar volumes*
V_f = *displacement space*
V_{max} = *maximal volume*
$x \in \mathbb{R}^n$ = *displacement vector*

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Superscripts

m = *number of possible bars*
n = *degrees of freedom*
S = *number of scenarios*

Uncertainty Identification

At the beginning of each design process it is necessary to clarify the design task. In this case the task is to develop a robust high heel. First of all, an abstract definition of a high heel has to be given. Afterwards the relevant uncertainties need to be identified.

Definition and description of a high heel

In the context of this paper the high heel is an open lady's shoe with a heel height of at least 100 mm (approximately 4 inches), Fig. 1. Insole, outsole and seat describe the massive parts where the foot is placed. The heel, the top piece and the sole under the toe box transfer the force induced by the user's weight to the floor.

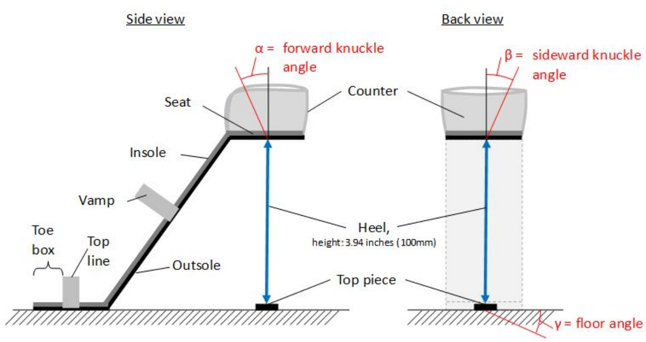

Figure 1. Basic definition of a high heel.

Robustness and uncertainty in the context of a high heel

A robust product "maintains a stated performance level of its properties in spite of fluctuations in primary and secondary inputs, the active environment, the operands and in human operation" (Andersson, 1996). In the meaning of the CRC 805, the entity of fluctuation is called uncertainty. As basis for a robust high heel design the occurring uncertainties need to be identified. It is obvious that the angles of the knuckle and the floor are important uncertainties occurring during the usage of a high heel. But there are other important uncertainties, e.g. sweat or the constitution of the floor which can influence the behaviour. A more or less complete identification of relevant uncertainties is supported within a systematic uncertainty analysis. To analyze uncertainties within the CRC 805 an Uncertainty Mode and Effects Analysis (UMEA) is developed (Engelhardt et al., 2009). With the application of this method occuring uncertainties and their effects should be identified, prioritized and calculated. Nevertheless the accomplishment is connected with certain effort. Given that the synthesis of a robust product is the main goal, the analysis of uncertainties is executed in a reduced way. Nevertheless the reduced way is based on the application of a process model (Kloberdanz et al., 2009) which is the basis of the UMEA. Using this model the relevant uncertainties can be identified. The knowledge of these uncertainties is the initial starting point for the development of a robust product.

Process model as basis for identification of uncertainties

In its simplest way the process model is based on a graphic visualization of a timeline in form of a labeled arrow. By parallel and sequential assembling and back coupling of several processes, the model chains and networks of processes can be described graphically. With the help of this structured division of process chains subprocesses can be regarded in more detail by the engineer. Uncertainties which occur within a separate process can be determined. Basically, the process model facilitates the engineer's communication and understanding of the usage processes. The results of the process modeling and the analysis of uncertainties constitute a conjointly aligned foundation for further steps of the design. At this point the process model arranges for a simple and quickly understandable documentation of the analysis results. For the design of a robust product the identified uncertainties are crucial. Within the design process these uncertainties must be controlled.

Identification of uncertainties of a high heel

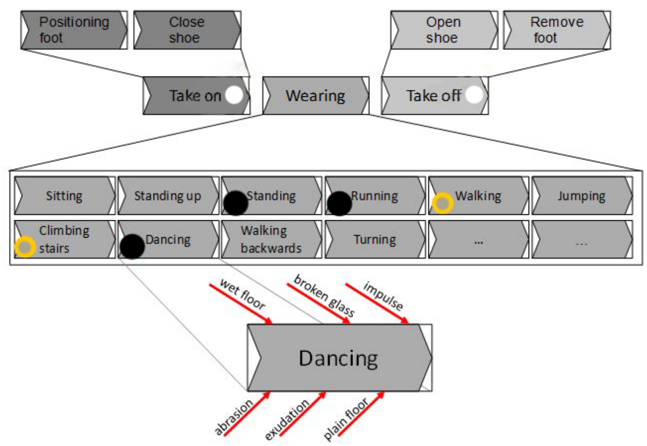

Figure 2. Uncertainty analysis based on a process chain model.

Figure 2 shows the usage processes that typically occur when using a high heel. Afterwards these processes are prioritized (white, orange and black bubbles) to detect the most important processes (black). It is necessary to keep this step manageable and to concentrate on the main processes. Therefore the analyzed processes need to be reduced to a manageable number. The processes a high heel is usually faced with and are supposed to be the most important uncertainties are marked with black. The less important processes are marked with white. Usage processes which can occur but are not important are not marked at all, e.g. sitting. Therefore it is not necessary to analyze these processes in a detailed way. The important processes need to be analyzed carefully. Figure 2 also shows one process (dancing) with identified uncertainties in detail. Uncertainties which can occur while dancing are for example wet or plain floor, broken glass, exudation, impulse and abrasion. These uncertainties can be dangerous for the person wearing the high heel and can probably lead to serious injuries. Therefore, it is important to design a high heel that is immunized against these uncertainties. Other processes are analyzed similarly. At the end of this design step a table including the identified and prioritized uncertainties can be created. The named uncertainties are standardized and not entire. Table 1 provides the basis for the design of a proper solution.

Table 1. List of identified uncertainties influencing a high heel.

Standardized uncertainties/disturbance
1. Soil condition
1.1 Plain floor
1.2 Porous floor
1.3 Bulk floor
1.4 Soft floor
1.5 Humidity
2. Exudation
3. Angle
3.1 Sidewise angular attaching
3.2 Sidewise angular attitude
3.3 Longitudinal angular attitude
4. Loading
4.1 Weight
4.2 Batches
4.3 Deviation
5. Foot anatomy
6. Shoe abrasion
6.1 Internal sole abrasion
6.2 Sole abrasion

Conceptual Design

In this step a conceptual solution for the design task is searched. Due to the robustness which is regarded as the most important requirement in this step a solution should be found to control the individual uncertainties. Principal concepts are deduced which control all identified uncertainties.

Search strategies and order pattern to design a robust concept

A basic possibility to control an uncertainty is the adding of a function within the product. This function is aligned particularly to control the uncertainty. This approach is obvious and easy to understand. On the basis of this approach a search for solutions can be carried out directly. Solutions can be found which can be integrated within the product. Certainly, this results in high efforts since for each uncertainty an additional solution is necessary. Moreover, interactions between several uncertainties and their solutions are neglected when using this approach. Despite these disadvantages this simple approach of adding a function is used. It directly leads to a creative and exciting intuitional search for solutions. This way of searching solutions is suitable when working in a creative and design-oriented team and therefore, it was suitable as a task for the competition Achilles High Heel. Especially, in connection with Robust Design the intuitive search for solutions can be supported systematically throughout certain strategies. Herewith, a guided intuitive search is carried out to come across suitable solutions as soon as possible. Basically, these strategies are based on the identification of the so called search fields. In these search fields it seems to be possible that an uncertainty occurs. Then products or ideas can be identified, which are robust for these search fields. Typically, these solutions cannot be assigned to the own design task directly because solutions are always dependent on the product. Therefore they are not suitable for a new design task. At first it is necessary to understand how the solution can control the uncertainty to derive an abstract principle. Using this principle, measures regarding the own design can be derived.

To discover new search fields which are interesting for controlling uncertainties three strategies can be defined:

"Related Products" strategy: Search for related products and identify which uncertainties they are usually faced with. Identify principles of controlling and assign them to your product.

Explanation: Solutions can be recognized quite easily in products that have a similar body but differ in their intended use. To find these products the engineer can set up a catalogue which contains every related product he knows and investigate the products concerning the occurring uncertainties. The advantage of this strategy is that the found solutions are quite close to an applicable solution for the own design task. Therefore solutions can be assigned easily and with little effort. Partially, for the assignment it is not necessary to work out a control principle.

"Related Environment" strategy: Search for environments where the regarded uncertainty usually occurs. Identify products which are robust in these environments and identify principles of control. Assign these principles to your product.

Explanation: Typically, special environments and special application areas ask for special requirements for technical products. These products control occurring uncertainties in a special way and can be used to identify the basic approach of control. If found products are not coincidentally related, the engineer must have a high ability for abstraction to recognize and deflect assignable principles for his own development task.

"Biological Principles" strategy: Search for natural environments where the uncertainty that must be controlled usually occurs. Identify biological creatures which exist inside these environments. Identify the principles of control and assign them to your product.

Explanation: Within nature many uncertainties can be controlled through proper solutions. On the basis of known uncertainties a sort of uncertainty-scenarios can be expressed. By means of this scenario biological environments can be searched which are similar to the scenario. Solutions that are developed by biological creatures within this environment can be used in terms of principles to realize a technical implementation. Today this technical implementation is known as bionic solution (Nachtigall, 2010). But today bionics rather shows the cleverly implementation of a biological principle into a bionic principle. As a real creative director for controlling activities the biological principle is more suitable than the bionic principle. The multiplicity of existing bionic solutions shows that this approach basically works. Furthermore, nature shows that very often several uncertainties can be controlled through one clever solution. Therefore this strategy can be used to find a solution which can control several uncertainties conjointly and thus effectively. Although this strategy at large basically offers a very interesting approach, some difficulties can be identified. At first, the engineer has to find out which biological environment is in accordance with his environment. Afterwards he has to know the existing creatures. Therefore this strategy is only limitedly suitable for the application through an expert of a technical field. Rather biologists should deal with the application of this strategy. Partly the borderline of science is reached when it is known that an uncertainty is controlled, but the solution is not known or cannot be explained. Some examples of these principles are given below.

Solution strategies for a robust high heel

The principles described in the previous section are exemplarily applied to the high heel designing task. Only a small number of examples will be given. The solution scheme in Fig. 6 gives an impression of the wide range of possible solutions.

- Example to “Related Products” strategy: The strategy of “Related Products” is realized through the comparison to a soccer shoe. A soccer shoe provides support and comfort for its carrier; properties which a high heel should possess. This is realized by robust support of the heel, since the ankle was identified as the major vulnerability. Additionally, a ravel is integrated into the sole to support the comfort. Wearing high heels implies a partially insecure support, which results from the minimal walking surface. Usually, the only connection between a high heel and the ground is the small area of the heel as well as the sole under the toe box. To provide a stable hold similar to a sneaker, the high heel shows a conical shaped walking surface, which connects the heel with the plateau.

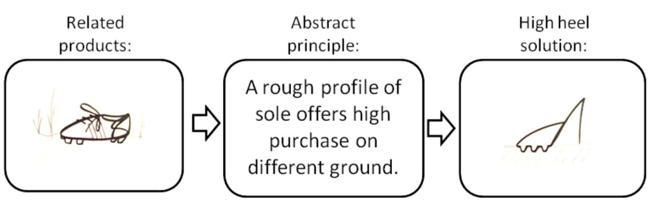

Figure 3. “Related Products” example.

- Example to “Related Environment” strategy: An orthopaedic splint enhances the stability of an injured leg and prevents from twisting one’s ankle. It is difficult to integrate a splint into a shoe because of aesthetic aspects. The designed high heel meets both requirements. The “Related Environment” strategy is used in the context of soil condition, e.g. wet, stony, soft or diagonal ground. Depending on the condition, resulting uncertainties and derived requirements are formulated.

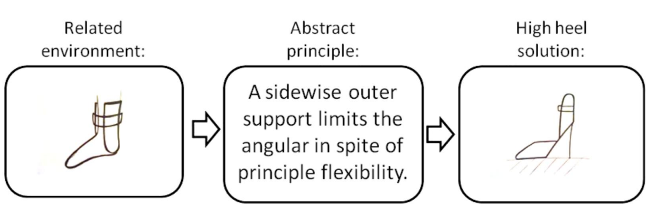

Figure 4. “Related Environment” example.

- Example to “Biological Principles” strategy: The “Biological Principle” is realized by using the example of an elephant foot. An elephant foot forms a circle, which consists of tendons and fat. Putting the foot on the ground, the foot area enlarges and forms a large walking surface. Lifting the foot, the surface area contracts again. This phenomenon can be transferred to the high heel. In this case the surface area is represented by the heel and its top piece. This function meets the requirement of a stable foothold and simultaneously fulfils the aesthetic standards.

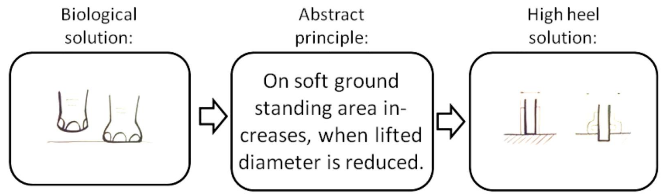

Figure 5. “Biological Principles” example.

Uncertainty solution scheme

After this step partial solutions for every important uncertainty can be generated. These solutions can be seen in figure 6, which shows an uncertainty solution scheme (see Pahl an Beitz, 2007). It contains the uncertainties horizontally and the ideas for solutions vertically. By analyzing this table, synergy effects can be seen when combining several partial solutions. By using this table the engineer can try to find combinations of partial solutions which are able to control several uncertainties simultaneously.

Figure 6. Uncertainty solution scheme for a robust high heel.

To demonstrate the search simply and clearly it is helpful to use the solution scheme in terms of a morphological approach. Here, every uncertainty is related to different possibilities of control in a row of a matrix. Thus, in the first column the uncertainties which need to be controlled are shown. In the fields of every row the solutions are shown which are basically supposed to control the uncertainties. These solutions are shown in the fields in terms of simple sketches. These sketches can be understood very easily and quickly. Moreover they offer a simple overview. This scheme can be used by the engineer to develop concepts that can answer the development task. Firstly, the scheme can be analyzed systematically by means of suitable questions to identify problems and potentials easier:

- Are there unfilled rows? It is possible that within the scheme there are rows which don’t contain solutions. In this case a new, more intensive search has to be accomplished. If an intensive search is already accomplished it has to be proved whether it is possible to leave the uncertainty uncontrolled without provoking a reduction of robustness.

- Are two or more rows widely identical? If there are rows where widely all solutions coincide, it has to be checked whether both uncertainties coincide as well. Partly, uncertainties that are basically identical can be regarded as different during the analysis. In this case the uncertainty can be described consistently and the redundant row can be deleted. Otherwise the uncertainties can be combined because no solution is lost when deleting one of the rows.

- Do solutions exist which control several uncertainties? In this case this solution offers a high potential to control several uncertainties with little effort.

- Can two or more solutions be combined or are they similar? Even in this case it is supposed that several uncertainties can be controlled with reduced effort.

By using these questions the engineer can reduce the field of solutions and find notably interesting solutions. However it is the engineer's main task to gather notably interesting concepts through clever combinations and avoiding conflicts.

The concept's demonstration takes place as a simple sketch which is the typical tool for product development. Additionally, it appears that some control approaches are not easy to be demonstrated graphically. In these cases a short additional description is carried out.

When the combination via the uncertainty solution scheme is finished, a conceptual design containing several partial solutions can be generated. An example for this step is shown in Fig. 7, a sketch of a high heel which is robust against several uncertainties. Due to its broad sole the shoe is robust against porous, soft or bulk floor simultaneously. At the same time it has a high plateau against humidity and a heel similar to a spring to realize the robustness against batches and to balance the person's weight. Other uncertainties are controlled similarly by other properties. After this step a first sketch of a robust high heel is generated and the step of conceptual design is finished.

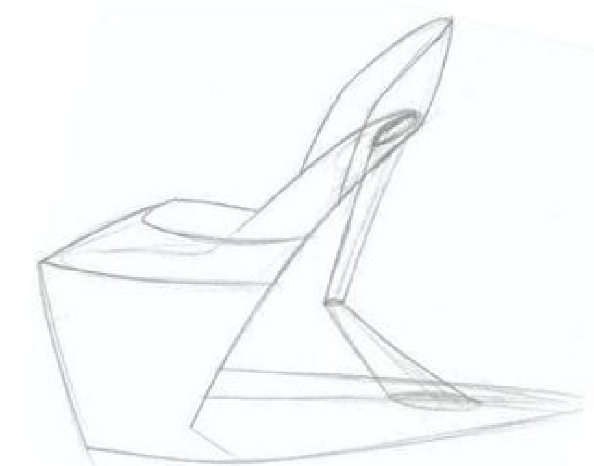

Figure 7. Conceptual design sketch.

Robust Optimization

Now that a design concept of the high heel is found, we are interested in the optimal design of the high heel. We want to use mathematical methods to find an optimal design. For load-carrying systems several approaches are known that can optimize a load-carrying structure for given loadings (see Bendsoe and Sigmund, 2003), e.g. free-material optimization, topology derivatives or truss topology design.

Robust optimization of load-carrying structures

Since in the case of optimizing a high heel under uncertainty, whose loading especially is uncertain, we decided to apply the concept of truss-topology design, where the concept of robust optimization with uncertain loading parameters is well-understood (see Ben-Tal and Nemirovski, 1997) in contrast with other known methods where the problem of uncertainty in the parameters is either hard to handle or appropriate concepts are not known.. In truss-topology design a ground structure consisting of nodal points (some of them are fixed, the others define the displacement space V_f with n degrees of freedom) and m possible connections between these nodes is given.

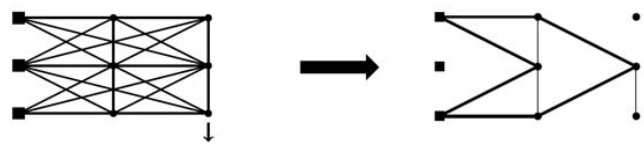

Figure 8. Left: ground structure of a truss, right: optimal design after truss topology design.

For a given load $f \in \mathbb{R}^n$ the aim is to find the optimal bar volumes $v \in \mathbb{R}^m$, such that the compliance $c_f = \frac{1}{2} f^T x$ is minimal. The vector $x \in \mathbb{R}^n$ describes the displacement of the free nodes obtained via Hooke's Law ($A(v)x = f$) with $A(v) \in \mathbb{R}^{nxn}$ being the stiffness matrix of the truss described by bar volumes v. This leads to the following optimization problem :

$$\begin{aligned} \min_{v \in \mathbb{R}^m} \quad & \frac{1}{2} f^T x \\ \text{s.t} \quad & A(v)x = f \\ & \sum_{i=1}^{m} v_i \leq V_{max} \\ & v \geq 0 \end{aligned} \tag{1}$$

The two last constraints guarantee that the total volume of the material of the structure is less than a given limit V_{max} and the bars have a positive volume $v \geq 0$. As explained before, the parameters (especially the load f) are uncertain. A typical problem in truss topology design is a result which is optimal for a given load f but unstable for a slightly different loading $\tilde{f}$ (see Ben-Tal and Nemirovski, 1997).

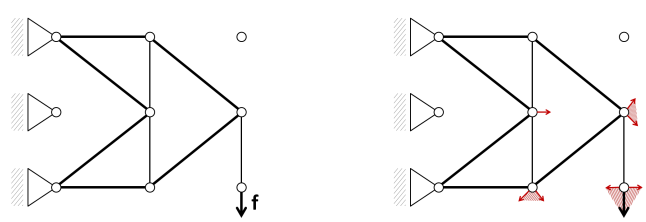

Figure 9. Left: optimal truss for a given loading scenario, right: not stable for small disturbance loads.

Therefore, the approach of robust optimization is used, which minimizes the worst-case compliance over all loading scenarios $f \in U_f$ for a given uncertainty set U_f. This leads to the following model of robust truss topology design:

$$\begin{aligned} \min_{v\in\mathbb{R}^m} \max_{f\in U_f} \quad & \frac{1}{2} f^T x_f \\ \text{s.t.} \quad & A(v)x_f = f \quad \forall f \in U_f \\ & \sum_{i=1}^{m} v_i \leq V_{max} \\ & v \geq 0 \end{aligned} \tag{2}$$

The question now is, how to describe the uncertainty set U_f? There are mainly two approaches - a polyhedral and an ellipsoidal uncertainty set. The polyhedral approach is also called multi-load truss-topology design, since the polyhedral uncertainty set $U_f^\Delta = \{f : f = \sum_{s=1}^{S} \lambda_s f_s, \quad \sum \lambda_s \leq 1, \quad \lambda_s \geq 0\}$ can be described via a finite number of loading scenarios $\{f_1, \dots, f_S\}$. This Multi-load-formulation becomes a large-scale problem if a full-dimensional uncertainty set for the n-dimensional displacement V_f space shall be considered, since $S = 2^n$ scenarios are needed. Another approach is based on an ellipsoidal uncertainty set $U_f^\circ = \{f = Qu : ||u|| \leq 1\}$ and leads to the semidefinite problem formulation (SDP):

$$\begin{aligned} \min_{v,\tau} \quad & \tau \\ \text{s.t.} \quad & \begin{pmatrix} 2\tau I & Q^T \\ Q & A(v) \end{pmatrix} \succeq 0 \\ & \sum_{i=1}^{m} v_i \leq V_{max} \\ & v \geq 0 \end{aligned} \tag{3}$$

For details, especially on the definition of the matrix $Q \in \mathbb{R}^{qxn}$ see Ben-Tal and Nemirovski (1997).

Robust optimization of a high heel

To apply robust truss topology design to design and optimize a robust high heel, an abstract ground structure of the high heel is necessary, consisting mainly of nodes (free and fixed) and bars. For this purpose, about 100 nodes are determined to represent the high heel abstractly. These nodes are linked through about 3000 bars to represent the possible material of the shoe. The abstract ground structure can be seen in Fig. 10, on the left. Based on this abstract ground structure several loading scenarios are applied which represent the prioritized processes found in the uncertainty analysis. For each process loading scenarios $f_s \in \mathbb{R}^n$ (with $n \approx 300$ degrees of freedom) are chosen, which represent the chosen process:

- f_1: standing (700 N orthogonal to the ground equally distributed on all nodes of the whole sole)
- f_2: standing on the ball of the foot (700 N orthogonal to the ground distributed only on the top nodes of the plateau)
- f_3: slipping (combined forces parallel to the sole structure)
- f_4: dancing (tilted forces in important nodes, e.g. at the seat, at the top or at the passage between plateau and insole)
- f_5: dipositioned foot (700 N slightly tilted to the orthogonal loads)

These loading scenarios are the basis for the uncertainty set, which is completed by additional small disturbance loads. In this case, an ellipsoidal uncertainty set is chosen with

$$U_f = \{f = Qu : \|u\| \leq 1\} \tag{4}$$

with $Q = [f_1; \cdots; f_5; \sigma e_1; \cdots; \sigma e_{q-5}] \in \mathbb{R}^{n\times q}$, a robustness factor $\sigma > 0$ and an orthogonal basis $e_1, \dots, e_{q-5}$ in the orthogonal complement to the subspace spanned by the forces $\{f_1, \dots, f_5\}$ in $\mathbb{R}^n$.

When the uncertainty set is defined, robust truss topology design can be used to receive the following optimal robust design, see Fig. 10, on the right.

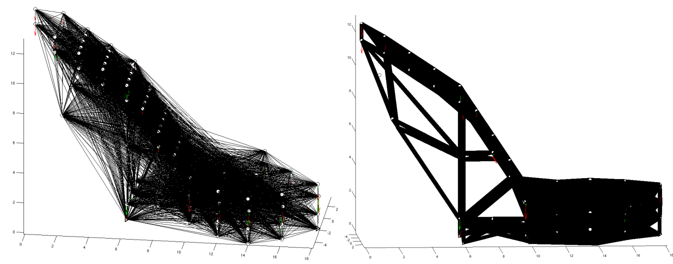

Figure 10. Left: ground structure of the abstracted high heel, right: optimized high heel after robust optimization.

The result is an optimal truss which provides information about the optimal material allocation. Since the design of a high heel aims to be most aesthetical, which means finely wrought, we are interested in a design which uses as sparse material as possible. The optimized structure is the design with the fewest material needed to control the given uncertainties. But of course, a designer might prefer a somehow different design.

Visualization of Uncertainties in CAD-Models

The visualization of uncertain product properties is given in a CAD-system. Part of this concept is the methodology of parametric and knowledge-based design. The identified uncertain product properties resulting from manufacturing are mapped on the modeling parameters of the CAD-model. Constraints between parameters present dependencies between uncertain product properties and allow visualizing the effects and chain of effects. This potential allows a variation of geometry in the lowest and highest border of the given value of deviation and the resulting effects. The resulting parametric CAD-model structure can be used for furthermore simulations. For more details on parametric and knowledge-based CAD-design see Mosch, Sprenger and Anderl (2011). The design of the high heel, which is deduced by a mathematical optimization process, is created as a CAD-model. All the prioritized functions to meet the requirements are visualized and integrated in the model.

Figure 11 shows the finished model of three different design approaches of a high heel. It is noticeable that the counter is extremely high to support the hold of the heel. The top piece and the plateau are linked together and result in a dynamic form. The sole design provides a large walking surface, which decreases the potential for uncertainty caused by different soil conditions. In total three different design solutions are created, which are assessed regarding their robustness against the identified uncertainties. These designs are modelled in CAD-programs like Siemens PLM NX and Catia. These CAD-models are the basis for printing realistic 3D-models via rapid-prototyping techniques.

Figure 11. CAD-models of three different designs.

Results and Conclusions

For the development of a robust high heel the combination of several methods has been used to find a proper solution which can control as much uncertainties as possible. At the end of the project several designs of a high heel were found. In Fig. 12 the rapid-prototyping-models of the designed high heels are shown.

Figure 12. Real RPT-models.

In Fig. 13 the shoes are evaluated regarding their robustness against the identified uncertainties. One high heel can be identified which meets the requirements and controls the uncertainties best. The standard high heel in the upper left square is not suitable to control all uncertainties, since the main focus is on the design but not on the robustness against uncertainty. The shoe in the lower left square controls the relevant uncertainties on a high level. Two other solutions are generated which can control the uncertainties on a higher level than the standard shoe, but they are also worse than the lower left square shoe. To empower the high heel to control as much uncertainties as possible the design apparently differs from standard high heels.

Figure 13. Radar chart for assessing the robustness of different high heel designs (upper left square: standard high heel).

Outlook

The applied methods are based on static loads. These methods can not capture dynamic loads. The application of dynamic loads especially of uncertain dynamic loads and other time dependent uncertainty (e.g. degeneration, abrasion) is due in future work. The team of CRC 805 focusses on dynamic aspects of uncertainty in the near future and an enlargement of the used methods on dynamical methods can be expected. Also the addition of real usage processes shall be covered. In this work, we stopped at the production of prototypes, which cannot be worn by test persons. This can be part of a future project where the back coupling of usage process and development process can lead to further interesting insights.

Acknowledge ments

The development of a high heel was a student's project guided by CRC 805 – "Control of Uncertainties in Load Carrying Systems in Mechanical Engineering" and was motivated by gender equality issues. The project was set up to increase the interest of young female and male academics for the topic of uncertainties in load carrying systems. We thank the German Research Foundation (DFG) for the financial support.

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