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Application of the Computational Design Synthesis framework for individualized car seats

Carl Steinnagel[a],*, Cem Bastimar[a], Paul Christoph Gembarski[a], Stefan Plappert[a], Patrik Müller[a], Roland Lachmayer[a]

[a] *Institute of Product Development, Leibniz University Hanover, An d. Universität 1, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49-511-762-5340; *E-mail address:* steinnagel@ipeg.uni-hannover.de

Abstract

The manufacturing capabilities of additive manufacturing allow great design freedom for mass customization of different products. This new solution space needs to be explored and served by engineers when designing individual variants of a product. Therefore, the methods of model generation for the individual variant with individual customer specific requirements must be improved to take advantage of this design freedom. This paper discusses the specific challenges of designing a customized car seat by showing its general process chain and the challenges associated with the design of foam replacement structures that offer the possibility to customize the stiffness of the cushion. A possible framework for the underlying digital process chain is then discussed. This framework manages model synthesis according to anthropometric data and safety requirements as conflicting requirements within various complex engineering correlations. In a case study, the chosen Computational Design Synthesis (CDS) framework is applied to the problem of designing an individualized car seat. Detailed descriptions of the concept for each block in the process chain are presented within the case study. The paper and conclusion discuss whether the framework meets the challenges of the application example and further steps for the project.

Keywords: Computational design synthesis, Mass customization, Model synthesis, foam replacements

1. Introduction

Despite the high priority given to individualized products by the market's need for innovation [1], there are no offerings for individualizing the ergonomics of car seats. This is despite the wide range of configuration options for seat covers, trim and in-seat comfort features. Despite these options and studies that show the benefits of adjusted seat pressure distribution [2], it is not possible to customize ergonomics like the hardness of the seat cushion. On the one hand, this can be justified by highly optimized Just-In-Time (JIT) assembly processes, in which each new part that has to be varied generates high effort and thus additional costs. On the other hand, there are no such options in the high-priced sports and luxury car segment, although car seats in this segment are still handmade in small quantities. In addition, these cars are marketed for a single occupant, either a sporty driver or a passenger being chauffeured in comfort.

Possible solutions to overcome technical limitations, such as those that exist in the production of seat foams, have been presented in previous work by the authors [3]. Conventional polyurethane seat foams based on a gas foaming process result in a uniform hardness throughout the foam. The replacement structures presented offer the new possibility of varying hardness within the cushion. Similar approaches already exist for other products, such as shoe soles [4]. However, in order to design and apply these foam replacement structures in practice, a digital design process is required that not only optimizes ergonomics, but also satisfies numerous safety requirements that are not present in the design of existing products such as

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customized shoes. The goal of this research is to conceptualize the underlying digital process chain and model synthesis based on related research and an existing methodological approach.

The product of the individual car seat (Tailored Seat) will be designed, built and distributed as part of the customized car in the following process chain: The process chain starts with the anthropometric measurement of the customer. This data is used to start the digital model synthesis of the foam replacement part. The next step is the optimization of the ergonomics based on known principles of seat ergonomics for perceived seat comfort [2]. The final step in model generation is the final design of the seat cushion. To meet safety requirements, the hip point is highly relevant. The hip point is the central measurement point in the overall design of the car and must not be shifted outside the permitted limits due to safety design aspects of seat. The design must therefore take into account the absolute seating position of the occupants, but this is not trivial due to the many non-linear relationships in the behavior of the seat cushion [3]. The design of the seat cushion must therefore be able to find an optimal solution in the conflict between the target requirements of ergonomics and safety. The seat cushion is then manufactured using a process selected from the pool of available additive manufacturing (AM) processes according to manufacturing constraints and design parameters. The final step is the assembly of the complete seat in a JIT process. Therefore, digital model generation is the key to the Tailored Seat process chain. This research first examines similar process chains that synthesize customized product models [5, 6] and the framework they use, the Computational Design Synthesis (CDS). The motivation and reasoning of the authors in using the CDS is discussed. Therefore, this step investigates whether the CDS can perform the individual model synthesis according to the given requirements in the outlined process chain. Subsequently, a case study will show how such a design task can be solved under consideration of safety and anthropometric criteria. The case study will present the core building blocks of the process chain in detail. This gives an overview of how individualized car seats can be designed in the future and which steps are necessary. In summary, the following research questions will be investigated in this paper:

- **1st research question (RQ1):** Is the Computational Design Synthesis (CDS) a suitable framework in the context of the outlined application example?
- **2nd research question (RQ2)**: What modeling technique can be used to integrate the chosen synthesis method with the given ergonomic and safety requirements?

2. Related Work

2.1. Ergonomic customization of seating

The modification of the seating surface is already mandatory for wheelchair patients in order to minimize the risk of developing diseases due to prolonged sitting [7]. The measurement of pressure distribution is essential to localize critical zones with pressure peaks. These can be individually adjusted, for example, by using seat cushions consisting of modifiable air cells via electronic valves [8]. In order to take a closer look at this measurement and optimization for car seat cushions, the basic principles of seat comfort are first considered. In his paper, the author Mergl [2] describes initial approaches for evaluating seat comfort and possibilities for optimization through targeted control of the seat pressure distribution. Mergl describes contact pressures, load percentages and gradients acting on the body in the contact zones with the seat as ergonomic criteria. The influence of these variables on seat comfort was investigated and summarized, and specific recommendations for permissible ranges of these values were given. As a further transformation step, the study involves the transfer and simplification of the seat pressure distribution to multiple body zones derived from a body map. A body map defines the loaded body zones into areas and serves as a benchmark for evaluating seat comfort. Subjects are interviewed to control the seat pressure to ensure comfort in these zones [2]. The possible use of this body map for an individual seat as well as further possibilities to access data and perform optimization operations should therefore be investigated. For this purpose, Mergl divided the seat surface into three basic body zones: the buttocks, the middle thighs and the front thighs. In these studies, the test subjects were only allowed limited seat adjustment during the test, as the seat pressure distribution would have been too strongly influenced by different seat positions. In order to achieve an optimal seat position for a tailored seat, different seat positions and the resulting seat pressure distributions have to be investigated already in the anthropological measurement phase [2, 9]. Since a local variation of the seat hardness of conventional seat foams is almost impossible due to manufacturing restrictions, a seat cushion with the current state of the art cannot optimally meet the target values recommended by Mergl.

Since the outer metal structure of a car seat is very complex and costly to modify due to safety-related crash tests, the seat cushion alone must provide sufficient seat pressure variation within the given space constraints to create an individual car seat. The authors Steinnagel et al. [3] have already presented solutions to replace conventional seat cushions made of PU foams with innovative, additively manufactured foam replacement structures made of thermoplastic polyurethane (TPU). These show almost identical deformation behavior compared to conventional PU foams. Additively manufactured products made of flexible materials such as TPU are already well established in the footwear industry, where the design of the internal structures can be used to control, among other things, the stress distribution on the sole of the foot and the energy absorption behavior [4, 9, 10]. The existence of different shore hardnesses of TPU is advantageous for seat cushions to realize a desired initial seat hardness. In addition, the use of internal structures makes it possible to adjust the hardness of the seat cushion precisely to the customer's requirements. The structures can be customized by changing the wall thickness and cell size, as well as the distribution of the material within the unit cells [4]. In this way, the required seat hardness can be achieved with independent adjustment of the above parameters, although there are coherent influences, e.g. in the surface quality of the structures [3]. This freedom in the design of a seat cushion offers new opportunities for product individualization in the field of car seats, but also new challenges in the design process. In order to use ergonomic and design knowledge for model generation, the design synthesis has to be formalized in a framework. Here, the parameterization of the internal structures is used to fulfill the ergonomic requirements of the seat cushion according to the customer-specific anthropometric measurement data.

2.2. Framework for design synthesis

A challenge of model synthesis is to describe the largely nonlinear design contexts and multiple optimization strategies within a multi-objective optimization with competing design goals. In this context, Computational Design Synthesis (CDS) describes a well-known methodological approach in which pre-developed design tools and elements support the solution of design problems [11]. Here, the algorithmic design process shows advantages over conventional Computer-Aided Design (CAD) software in terms of fast and effective design changes to new concepts [5, 6]. Figure 1 describes the basics of CDS, which is divided into four elementary building blocks: Representation, Generation, Evaluation, and Guidance [12].

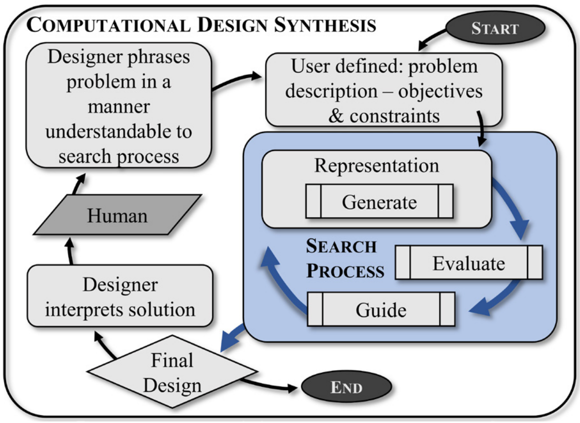

Fig. 1: Overview of a general CDS based on [12]

In addition to the boundary conditions, the design problem must first be described, which is basically categorized into form, function, and structure problems. Based on the defined design problem, the scope of the CDS is checked in a knowledge domain, where e.g. previous solution proposals are described [12, 13]. In order to generate solution proposals for the design problem, it has to be defined whether a random initial solution is sufficient or whether a design optimum is required. The evaluation process checks whether the constraints defined at the beginning are fulfilled and whether the generated design solution is admissible. An established evaluation method within CDS is finite element analysis (FEA). In the final step, guidance is used to provide feedback to the system and to control the rest of the CDS process. If the target values defined at the beginning are not achieved with the current design solution, the elementary building blocks "Representation", "Generation", "Evaluation" and "Guidance" are run through in a further iteration loop. The final design solution is interpreted by a human and, if desired, adjustments in the boundary conditions and parameter settings are made to perform further iterations [13]. The CDS method has already been successfully applied to product development in the field of medical technology. The authors Müller et al. [6] show in their investigations that additively manufactured hip endoprostheses can be generated and the bone ingrowth can be controlled specifically for the individual patient by controlling the internal structures. An advantage of the chosen CDS method in the generation of hip endoprostheses was demonstrated by the fact that the implants could be quickly adapted on the basis of patient-specific computed tomography (CT) scans. In addition, CDS can be improved and modified at any time, so its use for other types of prostheses could be recommended. In their work, the authors Biedermann et al. [5] use the CDS method for the design synthesis of additively manufactured multi-flow nozzles. By component decomposition of the model and development of design elements (e.g. wall thickness), the complex components can be quickly and efficiently adapted to new model variants and requirements and analyzed with respect to their additive manufacturability and performance using computational fluid dynamics (CFD). However, a high level of expertise is required to ensure that these benefits are translated into effective design modifications.

3. Structure and Method

The structural approach of this paper, which is used to answer the research questions (RQ 1&2), consists of five steps: First, the motivation and problem identification were explained in the introduction and the basics of the Tailored Seat. The research problems to be solved were summarized as research questions 1&2. In the second step, the possible framework CDS was explored in Section 2.2. In the third step, the justification of the framework will be done, thus answering the first research question. Then, in the fourth step, the case study will answer the second research question and present the detailed conceptualization of the digital process chain of the application example. Finally, the results are evaluated and the contribution of this paper is summarized.

The CDS method has already been introduced in Section 2.2. The authors Müller et al. [6] and Biedermann et al. [5] have already given a variety of reasons why they chose CDS as a synthesis method. For Müller et al. [6], the reason for choosing CDS as a framework for generating implants is the ability to respond to a highly patient-specific design problem. This is also a decision criterion for this framework in the application example Tailored Seat, as each seat variant is based on an anthropometrically defined design problem. The general development methodology should be able to react to different seat cushion types from different seat models and not only allow different individual constructions of the same output type. This task description is very similar to the task of Müller et al. to react to different implant positions in the body. In particular, the use of the CDS by Biedermann et al. in the area of multi-flow nozzles has demonstrated the potential of this framework. Specifically, Biedermann et al. used the framework shown in Figure 2, modified from the CDS. This modified framework combines the individual steps in the following blocks:

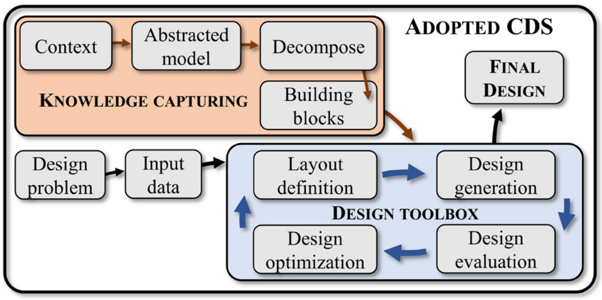

Fig. 2: Overview of CDS framework based on [8]

The separation of block design evaluation and design optimization in the iterative process provides the possibility of direct comparison with given safety requirements. Furthermore, a synergy of internal optimization and external numerical simulation was chosen, which will also be implemented for the process chain of the Tailored Seat. The variant of the framework shown in Figure 2 is used for the case study in the following chapter.

The iterative procedure in the design toolbox should allow to sufficiently optimize the conflicting requirements of comfort (optimal seat pressure) and safety (optimal seat position) described in the introduction. Similarly, the methodological structure of an input data path, consisting of the definition and generation of input data, fits very well with the planned data collection and processing in the context of seat pressure measurement. In conclusion, the path of knowledge acquisition can also be well reflected in the approach of previous project work. With the selection of a framework for model synthesis, the first research question is answered. The framework will now be executed in the case study to answer the second research question in this section.

4. Case Study: Application of the CDS

As a case study, the conceptualized modules for the digital process chain based on Figure 2 are presented below. The focus is on the design toolbox of the CDS and the associated collection and processing of input data. The knowledge capture takes place in parallel in independent work packages, therefore only the interfaces of the captured knowledge to the actual digital process chain are shown here.

4.1. Design problem

The design problem is acquired and processed according to the procedure shown in Figure 3. In the first step, after the seat pressure measurement, the linkage between the seat pressure distribution data points and the body map is performed. In this process, the seat pressure distribution is transferred to the top of the CAD model of the seat cushion, taking into account three-dimensional distortions. The subsequent transformation step from measurement data to body zones is made possible by a geometrically pre-adjusted body map. This is geometrically modified based on the customer's body dimensions (classification by height and weight) and analyzed using expert knowledge and specified load gradients in the seat pressure distribution. After areas are defined according to the body map zone boundaries, averaged load values are applied to the body map. Based on these averaged load values, a rule-based plausibility check is performed to confirm the input data for the subsequent optimization process. Using the simplified representation and data base of the body map and its zone definition, various plausibility aspects can now be checked to verify the correct seat position and seat adjustment.

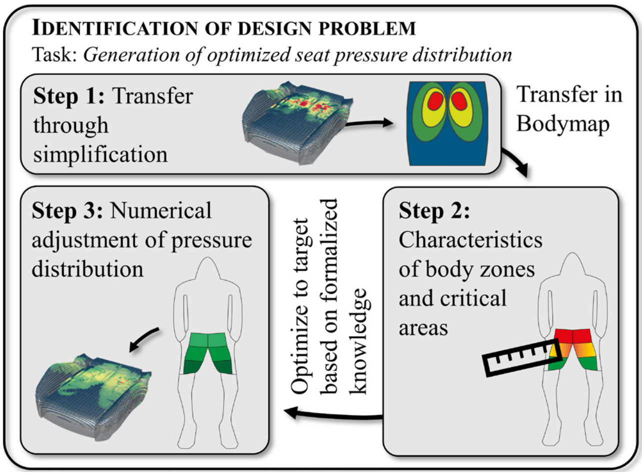

Fig. 3: Design problem definition

This approach is used to improve the limited use of different sitting positions and lack of optimization by deliberately changing the sitting position performed by Mergl. For example:

Is the client's cumulative seat pressure and weight coherent? If not: Check the back angle in measurement and enter the body weight.

Are the zones in the expected position and orientation to the specific seat coordinate system? If not: Check the customer’s position in the seat and the basic seat adjustment setting.

The aim is also to check these rules in real time during the measurement of the customer, as this is the only way to ensure the basic adjustment of the car seat and the elimination of an disadvantageous seating position through continuous feedback and a constant display of the filled body map. This is particularly important because the customer is in the measuring seat before the car is purchased. A rule-based implementation would eliminate the need for time-consuming computations. In this way, a structured case base can be built up, which makes it possible to gain knowledge about ergonomics and measurement errors in the development phase and during the runtime of the product.

With the verified input data, the ergonomic optimization as a goal for the design toolbox can now be carried out. This is done first by checking the criteria for seating comfort according to Mergl [2] in the values of the body zones. If certain comfort rules are violated and a potential discomfort is detected, an algorithm is used to determine how the load can be redistributed to minimize the discomfort. In the long term, the generated data and the collection of long-term experience values will be used to build up a case base to further increase the prediction accuracy. This new optimized seat pressure distribution, which is derived from the optimized body map, as well as the associated load redistribution, will serve as the design target. The design problem for the synthesis of the individualized seat cushion is therefore to achieve the optimized seat pressure distribution without violating the required position of the hip point.

4.2. Input data

To complete the objective description for the design toolbox, two intermediate steps are required to complete the input data set. These steps are illustrated in Figure 4. The known hardness of the reference foam on which the seat pressure measurement is performed provides additional data for the optimization process. From this, a substitute model of the buttocks can be derived, as well as the reference seat position for validation according to safety guidelines. To adapt the FE dummy, the model is based on both the geometrically adapted body map and the local seat pressures. From these, equivalent stiffnesses for the buttocks can be determined and transferred to the geometrically adapted FE equivalent model of the buttocks.

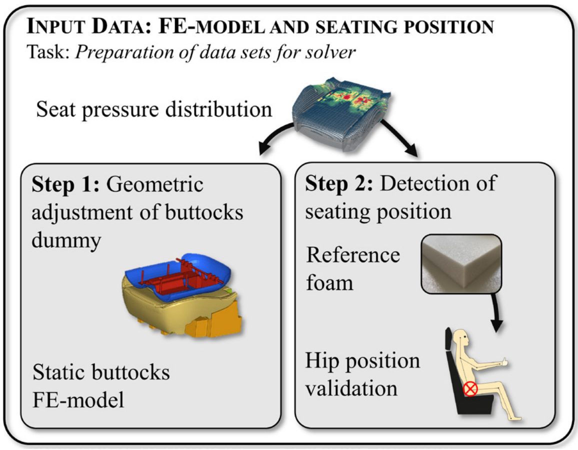

Fig. 4: Input data preparation

The second step also takes place in FEA, where the reference foam is subjected to the seat pressure to determine the seating position. The sum of the buttock’s deformation, which can be reconstructed from the surface load on the known foam hardness, provides precise information about the seating position before the seat cushion is adjusted, as well as further in the design process.

These two steps serve as a proposal to use this reference seat position, comparable to the hip point, as a core aspect for virtual safety validation. The hip point is the central design point for the entire car body. A possible virtual validation of each individual car seat, which has not yet been approved by the legislator, will therefore most likely be based on a representation of the hip point. Therefore, the design and validation in the digital process chain should include this as a central design point from the beginning. This virtual safety validation of the seat cushion behavior is crucial for the success of the individual car seat, as the need for physical validation (crash test) would significantly increase costs.

4.3. Design Toolbox

The design toolbox, as the core building block of the CDS, is provided with both the case-specific input data and the captured knowledge (Fig. 5). This includes, for example, the behavior of different foam substitutes and their specific optimization strategies. The individual problem is provided in the form of a target requirement for the comfort optimization.

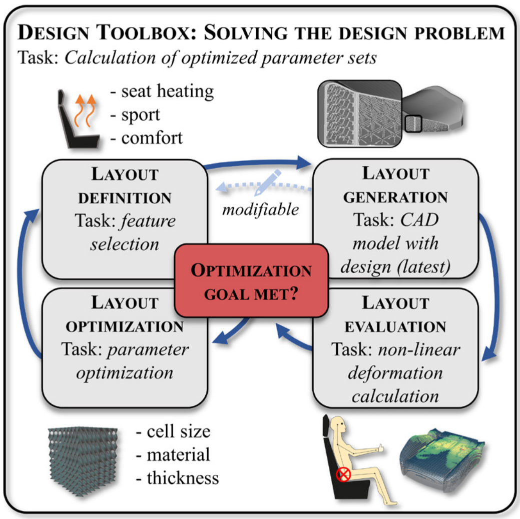

Fig. 5: Design toolbox layout

The first iterative step, the layout definition, consists of externally specified criteria such as the selection of seat functions, the equipment line, but also criteria such as the selected manufacturing method. The selection can also be made automatically from the vehicle configuration data and stored process knowledge. The modeling of the initial solution and all further solutions in the optimization loop takes place during layout generation. The initial solution is a layout that directly reproduces the hardness properties of the PU foam on which the seat pressure measurements were made. All other models in the layout generation follow the solution of the next optimization loop performed in the layout optimization. In both cases, layout generation fills the target volume of the seat cushion with parametrically controlled internal structures of the desired dimensions and hardness, as well as selected design elements from the layout. The generated model is used to check the seat position and the seat pressure distribution resulting from the model in the layout evaluation. The nonlinear deformation calculation is performed in a separate FE program. A homogenized FE model, which represents the inner structures of the seat cushion in a simplified way by correlating properties by representing them as solids of equivalent properties, determines the total deformation of the seat cushion (hip point or reference point) as well as the resulting seat pressure distribution. For this purpose, the FE model is loaded using the adapted FE buttock dummy shown in Figure 4. Based on the results obtained and the deviations found between the desired seat pressure distribution (result of 4.1) and the distribution simulated with the latest design, a specific parameter optimization strategy is carried out. This strategy varies the hardness parameters in the cushion according to the manufacturing process selected in the layout. For example, in the case of powder-bed additive manufacturing, the wall thicknesses of the structures can be precisely controlled, while processes based on material extrusion require a different strategy, in this case adjusting the cell size. This optimization loop iteratively transforms the seat pressure distribution from the initial mapping to the optimized pressure distribution.

If the required abort criteria (seat pressure distribution and seat position) are not met, the iterative loop starts again with a new generation of the current CAD model in the layout generation. This fills the target volume with the new set of determined structural parameters. If the selected method does not reach the abort criteria after several iterations, or if the modeling fails, another step back in the toolbox is required to manually adjust the layout definition. If the abort criteria are met according to the design problem, the final model is exported, manufactured and completed in the custom car seat. Due to the flexible nature of the layout definition and the general possibility to change the seat cushion shell, this concept of the CDS toolbox will be able to react not only to changing input data (e.g. varying seat pressure), but also to different seat cushion shapes (e.g. seat versions, trim lines). This makes the creation of the toolbox a long term investment that can not only serve multiple product lines and generations, but could also be used to create any shape of cushion with precisely adjusted stiffness, which would benefit the engineering of any car seat.

5. Evaluation and Contribution

The contribution of this paper shows the conceptualization of a digital process chain for the generation of individualized car seat cushions. This research was conducted due to the unique problem of a conflicting multi-objective optimization of the product with strict and diverse safety regulations. In conclusion, the case study presents a concept and detailed task descriptions for the modules to solve the task associated with the design of such an individualized cushion.

The successful application in the case study thus strengthens the CDS-framework in its conception. An example of this is the processing of input data enrichment and compliance on the basis of expert knowledge, which represents an additional linkage of the input data to the knowledge base. This can be in contrast to other applications, can be carried out autonomously. The conceptual design has shown how conflicting goals can be dealt with and how a possible validation, which is not yet anchored in legislation and automotive regulations, can be implemented.

So far, sub-systems of the concept shown in the case study have been successfully implemented and tested in stand-alone applications, e.g., lattice modeling, parametrization of lattice information, homogenized FE-analysis. The next step is the full implementation of these subsystems in the digital process chain using tools such as Rhino/Grasshopper and Abaqus FE. The challenge in this step will be to establish communication and information shared between the steps and to test the overall viability of the optimization. In this way, problems that were overlooked in the conceptual digital process chain can be solved. In the last step, the entire process will be tested with automated sample design based on edge-case anthropometric data to see the limitations in the overall digital process chain and product viability. In this way, the viability of the digital process and the real-life implementation of the product will be tested and advanced to make the ergonomic benefits available to a broad group of buyers.

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