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To cite this article: Haibing Li and Roland Lachmayer 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **408** 012035

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Generative Design Approach for Modeling Creative Designs

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Abstract. Design problems with variable requirements force designers to explore multiple alternatives between problem space and solution space of a design task. Despite several methods have been already proposed, CAD models hardly meet these variable requirements. To close this research gap, this study develops a generative design approach, addressing the automation of designing alternatives by capturing design knowledge into a set of design elements. These elements use essentially knowledge-based parametrics in terms of design requirements. Such design elements are used to assist designers in the creation of required design variants. Thus, the exploration of design alternatives is transformed into configuration of desired design elements. As a result, the invested time in routine work is reduced and designers are able to concentrate on the exploration of required design alternatives. Moreover, the output configuration also offers potentials in computer-aided optimization, since the design elements not only capture the design knowledge, but also incorporate manufacturing restrictions. At last, this approach is illustrated by taking a bicycle peddle crank as an example.

1. Introduction

Product design is a multidisciplinary activity that requires constant exploring, optimizing and testing until an efficient solution is designed and built. Such activities should be agile and well-organized to provide enough flexibility for adapting to constantly evolving markets. Thus, the key steps of these activities are that designers are required to explore multiple alternatives between problem space where all the design requirements are described, and solution space that consists of all possible design solutions for the design task [1]. Besides, ongoing understanding and new knowledge require continuous modification of concepts and constraints throughout the design lifecycle, inevitably impeding the search for alternative designs [2]. Hence, it is needed a robust design method to generate dynamic geometric models that can be easily adapted to satisfy changes and increases the number and diversity of design alternatives. As a result, computer-aided design (CAD) has been long accepted as an essential enabler, providing formal validation methods to create efficient and adaptable models that guarantees the delivery of truly innovative products in a timely and cost effective manner.

However, despite several computer-aided design methods have been proposed, e.g., parametric design [3], feature-based design [4] and knowledge-based design [5], CAD models hardly meet these variable design requirements, because design is an iterative process, which is limited to a reduced number of constraints and simple relations among parameters that are clearly insufficient to explore multiple design alternatives. To close this research gap, this study develops a Generative Design Approach (GDA) to address the automation of design alternatives by capturing design knowledge into a set of design elements, which are later used to assist designers in the creation of required design alternatives. As a consequence, the invested time in routine work is reduced, allowing designers to concentrate on the exploration of required design alternatives.



2. Related works of generative design

Generative design is a design method in which the exploration of a new design is described as a series of transformations from an early initial data to a large number of possible knowledge-integrated designs, which have high qualities that meet the design requirements in the best possible way. Hence, after studying the techniques that support generative design, Cui overviewed the framework of generative design by several examples, a design method is presented using automatic transformation algorithms of AI nature to support the exploration and generation of design alternative solutions [6]. Singh proposed an integrated generative design framework for supporting design exploration and creativity by reviewing five generative design techniques [7]. The potential challenges and building strategies towards developing such an integrated framework are discussed in this research as well. Krish developed a generative design method that is focused on generating multiple variants and alternatives of one proposed product without human intervention [8]. This method is suitable for complex multi-criteria design problems where important performance criteria are un-computable. However, in their works, there is a significant burden of selecting amongst a large quantity of design alternatives due to the lack of an evaluation method.

In the aspect of generative design implementation, Barros implemented a method for exploration of solutions for chair generation in the age of mass customization [9]. This method leads to a better exploration of design alternatives, stimulates multidisciplinary collaboration and finds potential best solutions prior to the manufacturing phase. Bagassi revised the improvements of generative design principles within traditional design procedures in aircraft design [10]. Thus, the output is not only a suitable design solution, but also a family of different results that designers could properly select and modify. Gulanova developed a generative design application within complex CAD systems, which provides an automatic adaptation of detailed design in case of design modification [11]. This is capable to improve data quality and reduce development time through collaborative workflow. However, this method is only applicable with enhanced CAD systems with parametric associative surface modeling and the designer has to follow predefined methodological rules.

3. GDA formulation

Generative design is formulated to support the automatic generation of a large number of design solution alternatives with computer algorithms that can be selected and controlled by designers. Despite the existence of many success stories in the area of generative design, the design procedures are still not well-documented. For that, in this paper the design procedures of GDA are formulated by generating design alternatives in a closed loop, as shown in figure 1.

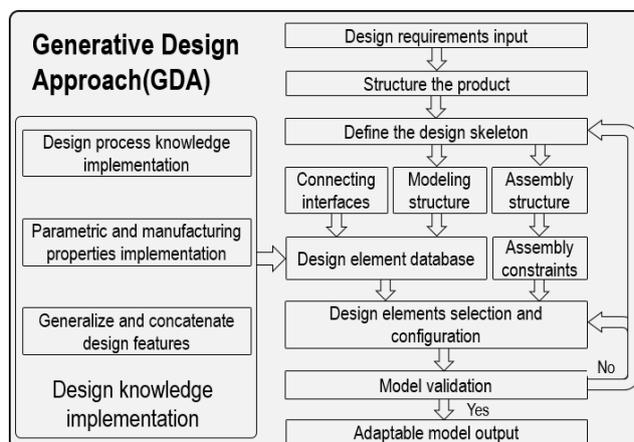


Figure 1. Framework of GDA.

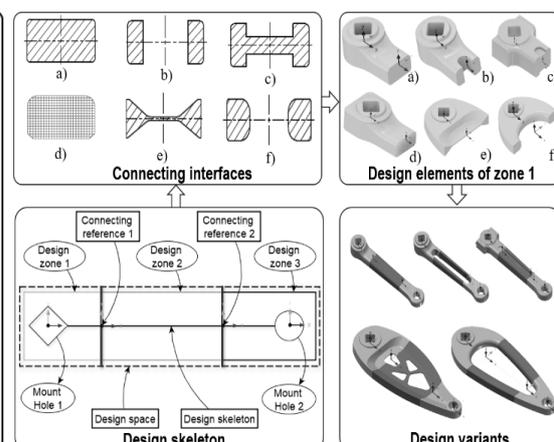


Figure 2. Bicycle peddle crank design by GDA.

According to the design requirements, a product is structured and analyzed by its functionalities from a systematic point of view, dividing the product into several design zones. After researching the product features and functions, a design skeleton is established, where the modeling structures,

connecting reference planes and assembly structure are defined. Following the design skeleton, the connecting interfaces and design elements can be created. Desired design elements are linked through the design skeleton and configured via multiple levels of parametrizations. This parametrizations and configurations of design elements enable the generation of a large number of design alternatives that are robust against topological changes, which is beneficial for computer aided optimization. At the end, the exploration of the possible design alternatives is automated to find the best design solution.

4. GDA implementation: Bicycle peddle crank design

4.1. Design element database creation

Design element is the essential building block of the GDA. A design element in GDA is normally a CAD file that can be defined as “the representation of a family of objects that share the same topological constraints but have different geometry” [12]. The design element needs to capture the design intent, which is defined as “that is a set of geometric and functional rules, which the final product has to satisfy” [13]. The building sequence of a design element plays also an important role in determining its robustness and adaptability. Therefore, the creation processes of a design element are in detail clarified later in this section.

4.1.1. Design skeleton. The idea of a design skeleton is based on the observation that a new product is often comparable to preview ones, but with different dimensions and element positions. The result of a design skeleton is defined based on reference elements, such as points, axes, planes and surfaces, which provides either a modeling structure to create a design element or a reference to drive the main dimensions and positions of the design elements, e.g., an assembly structure. A well-constructed design skeleton contains all critical positions and dimensions, which are controlled via multiple levels of parametrization inside the model [14], which offers the following advantages:

- Specification-driven design: Key design information is stored in the design skeleton. Design constraints are defined within the skeleton to help allocate space for the design elements.
- Design changes management: The design skeleton helps to manage high-level design changes and propagates them throughout the assembly. Modifications of the design skeleton propagates the changes to all related design elements and sub-assemblies. This provides designers more control over changes in product development.
- Collaborative design: Key information stored in the design skeleton can be associatively copied into the appropriate design elements used in the product. Different designers can then edit the design element separately. Changes during the design can be made in the design skeleton and all models will update to reflect these modifications, realizing high degree of collaborative design.

To use the design skeleton properly, design elements are constrained using only the skeleton as reference for positioning and parametrization. The modification of the design element dimensions is done by manipulating values of the design skeleton parameters as well. As shown in figure 2, the design skeleton of a bicycle peddle crank contains 2 mount holes, which are the most important criteria that have to be considered. According to its structure and its functions, this crank is divided into 3 design zones, resulting in a skeleton that is defined by 4 local coordinate systems. These coordinate systems address the assembly positions as well as the orientations of all 3 design zones. Likewise, the connecting reference planes are also defined at every local coordinate system to set a reference for modeling and placing different design elements. Based on this skeleton, each design zone of the crank has a unique modeling structure, which is already linked to neighbor design zones.

4.1.2. Connecting interface parametric design. The modeling structure coupled with connecting interface explores the design boundaries of every design zone, so that every design element represents an inherent fraction of a product. Thus, parametric design of the connecting interfaces of a design element plays a vital role in design element creation. Further, the connecting interface has to incorporate design restrictions, e.g., manufacturing restrictions [15], so as to increase the robustness

and the diversity of design elements. Going into details, parametric design of a connecting interface is identified by a shared set of parameters. On one hand, there are some fundamental parameters characterizing the shape information of a design element. On the other hand, there are special parameters characterizing the individual design information of the connecting interface. Besides, some parameters that have a limited number of values corresponding to design standards, e.g., DIN EN 10210-2 [16] for a hollow interface, should be defined as well. Therefore, a connecting interface is fully constrained by a set of parameters and integrated necessary design knowledge and restrictions.

4.1.3. knowledge-integrated design element creation. Design knowledge enables designers to setup a design, where the product is described in detail for the purpose of covering the allowable design space. Knowledge integration translates the design requirements to fully defined outputs via various methods, e.g., configuration concepts, formulas, macros and design tables. Thus, the knowledge related to a product is translated to a set of formulas and rules that describe its behaviors, so that the design requirements are formulated into a language that can be understood by the CAD system.

In figure 3, a creation example about the design elements of design zone 1 is presented. Here the design problem is how to balance the weight and structural stiffness of the bicycle peddle crank. The evaluation of the weight and stiffness requires geometrical models of the design. Normally, the evaluations are done with only a few design alternatives, since traditional parametric CAD modeling techniques hardly cover the whole design space. However, the evaluation here is carried out through different connecting interfaces by integrating different manufacturing techniques, e.g., lattice interfaces for additive manufacturing. With the help of a modeling structure, a design element addresses both design knowledge and manufacturing knowledge. When a design element is established, a check is made by design requirements and design guidelines to verify if the current set of parameters is allowed or conflicting. A design element is finished if all parameters are solved and no conflicts with the requirements on the weight and stiffness of the crank are found. Through detailed calculation, the designed elements have the same function but different topologies, which are saved together as a design element database for design zone 1 (figure 2).



Figure 3. Knowledge implementation via various methods.

4.2. Model configuration and optimization

Based on different design requirements, design elements have to be assembled together. The possible design solutions are created by a combination of design skeleton, connecting interface and design element database. A computer-aided design tool that supports parametric design in parts and assembly is necessary to facilitate the implementation of GDA. During the design process, the user selects the desired design elements from the database and a generative model is built up step-by-step by applying automated placing and assembling procedures according to the design skeleton and connecting interfaces. A configurator, e.g., a spreadsheet or a macro, is also programmed being responsible for selecting desired design elements from the design element database for feeding model generation. In order to ensure that the selected design elements are compatible with each other, a rule is defined with the knowledge integrated in logical expressions to determine whether they are compatible or not.

Figure 4 shows the generation processes of the crank. For that, Autodesk Inventor CAD system is extended with a CAD plug-in application that supports the generation of such a crank. In this application, by defining the connecting interfaces, the design rules behind will retrieve the corresponding design elements and configure those at the right place in Inventor, which is basically

done by inheriting parameters of the design skeleton to the design elements. Here these parameters are the positions and orientations of design elements. The local coordinate systems in the design skeleton aid for positioning design elements one after another and orient of them, so that a desired peddle crank is generated. In this way, different models can be created by changing the connecting interfaces. At last, the most relevant solution alternative is identified.

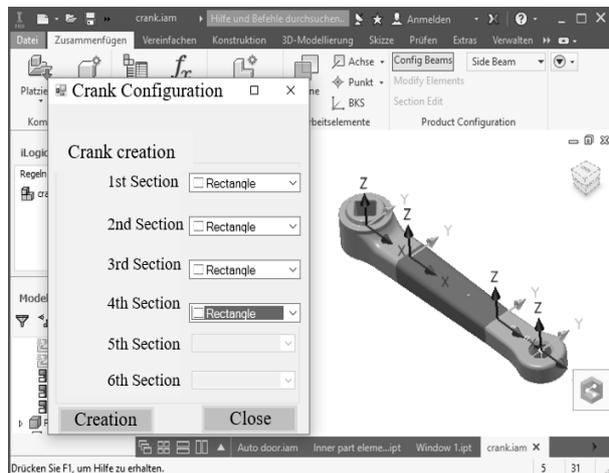


Figure 4. Model configuration.

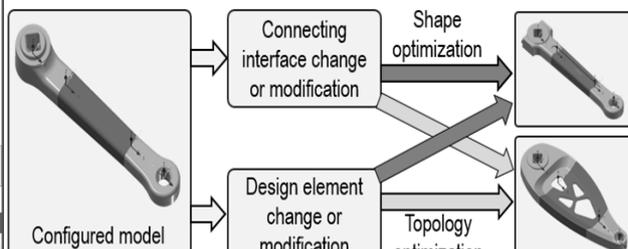


Figure 5. Computer-aided optimization.

The presented approach offers also possibilities for computer-aided optimization, since the design elements not only capture the design knowledge, but also incorporate knowledge of manufacturing restrictions (figure 5). On receiving initial results, designers will usually study the various options to refine the design skeleton and the connecting interfaces more accurately. With the help of the design element database, the designed model allows adding, deleting and modification of design elements or connecting interfaces throughout the product development process.

Basically, the parametrizations of connecting interfaces and design skeleton support parameter based shape optimization, i.e., the positions and orientations of design element as well as the parameters of connecting interface can be refined, realizing a parameter based shape optimization. Further, the design solution space is explored by topological design elements of every design zone. Therefore, the exchange of design elements leads to a topology optimization problem. The topology optimization by GDA is structured as the search for the design variation ranges within the design element database and the design knowledge by variable design rules, according to the design requirements.

5. Discussion

Design problems in GDA are represented as a design element configuration problem, where design solution alternatives are explored based on the design elements creation and configuration throughout the product development process. As discussed, GDA has the following advantages:

- Reduction of development time and cost: Through the use of limited computing, a large number of design alternatives can be investigated at the same time it might take to create one design using a more traditional approach, which is a timely and cost effective manner.
- Customize product development: With GDA, complex geometries specifically designed and optimized easily to suit an individual need are much more accessible than ever before.
- Provide optimization ability: Based on the parametrizations of design elements and design skeleton, computer aided optimization is easily implemented by either exchanging the design elements or manipulating the parametrizations of connecting interfaces or design skeleton.

However, there are also some negative aspects of GDA. It is clearly observed that GDA has an increased demand on knowledge of design engineers in terms of design element creation and

knowledge integration. Besides, in GDA, the focus is supporting knowledge for engineers to capture and formalize the necessary design knowledge rather than preparing the knowledge for end users.

6. Conclusion and outlook

The contribution of this research is the development of GDA, which supports the automatic generation of a large number of design solution alternatives. It does not only save time by exploring and storing all the necessary knowledge of the whole lifecycle through design skeleton and design element database, but also integrates CAD system through friendly user-interfaces that provide reliable technical supports. The output model is not only a design solution, but also a concept that the designers could manipulate that facilitates design optimization, because the design elements capture the geometric knowledge and incorporate design restrictions as well. Therefore, the optimization is structured as the search of the variation ranges within the design elements and the design knowledge by variable design configuration rules according to the design requirements.

After verifying GDA with the mentioned case study, the evaluation of the generated models still have to be investigated. Rather, in the application and example presented in this paper, design restrictions have been integrated in the design elements, so that the evaluation was left for the user to decide. In this way, the user can understand how to configure a satisfied outcome. Otherwise, the application will be exhausted when all the design rules have been applied. Nevertheless, an evaluation method will be developed in the future to suggest which design alternative is better than others. Another important issue will concentrate on the development of design methods and tools for a further integration of design knowledge, in which the manufacturing restrictions has to be implemented as well.

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