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TEMPLATE-BASED DESIGN FOR DESIGN CO-CREATION

Haibing Li[1], Paul Christoph Gembarski[1] and Roland Lachmayer[1]

[1]Institute of Product Development, Leibniz University Hannover,
Hannover, Germany

Abstract: Co-creation offers significant potential to improve innovation capabilities of both designers and customers. However, despite of the significant advantages, there is surprisingly little research providing detailed application knowledge and well documented examples that can be transferred to use cases relevant in industry. Therefore a template-based design approach that supports designers to explore a large design solution space is presented in this paper. After discussing the theoretical background for knowledge-based design, design templates, design solution spaces and their restrictions and the implementation of template-based design is discussed in detail. By the integration of design restrictions, a reusable knowledge-based design template library was established, which supports a user-friendly application of design co-creation. Thus the users or customers are involving in design to search for a large number of topological variants between the problem space and solution space. At last, this approach is exemplarily applied to the assembly of a beam structure.

Keywords: *template-based design, design co-creation, design template, design configuration, knowledge-based design.*

1. Introduction

Co-creation offers significant potential to improve innovation capabilities of both designers and customers. Co-creation benefits include: enhanced engagement of employees (Hatch & Schultz, 2010); better supply chain integration (Jüttner et al., 2010); improved shareholder commitment (Madden et al., 2006); and improved identification and satisfaction of customer needs (Reichwald & Piller, 2009). Business models in the field of mass customization take customer co-design as a basis (Piller, 2004; Gembarski & Lachmayer, 2017). In the context of co-creation, design knowledge integration is one of the central means for creating and sustaining competitive advantage in engineering design. Kohlbacher (2008) presented a concept of knowledge-based new product development in an effort to explain the role of knowledge in product development and the process of its co-creation, with a particular focus on the involvement of customers. Roser et al. (2009) described design co-creation as knowledge-based design process which is not just the interaction of how knowledge is created, shared and transferred between designer and user, but also as supports to create shared meaning and a satisfied design solution. However, despite of the significant advantages, there is surprisingly little research providing detailed application knowledge and well documented examples that can be transferred to use cases relevant in industry.

1.1. Motivation

Due to the growing number and variances of requirements, the design of complex products requires designers to explore multiple alternatives between problem space and solution space. During the product development process, designers are faced with the problem of selecting amongst a large quantity of designs but the designer is able to assess only a limited number of design solutions without cognitive fatigue (Buelow, 2002). For customers, who configure their individual product via internet technologies, this is even more complicated since they usually do not completely have the necessary design knowledge for assessing and judging alternative solutions (Reichwald & Piller, 2009). Here, technologies of knowledge-based engineering, e.g., product configuration systems, and knowledge-based design, offer great potentials because the relevant engineering knowledge is coded in the digital product models themselves (La Rocca & van Tooren, 2010).

Knowledge-based design (KBD) is a 3D modelling approach for product design to widely automate design tasks by reusing predefined methods, results and algorithms (Verhagen et al., 2012). The usage of templates to reuse knowledge and design solutions is a common KBD approach within today's product development. Current CAD systems provide functions to define design templates and to store or manage them in libraries (Gembarski et al., 2015). With the help of design templates, in contrast to traditional modelling strategies, a large opportunity for design co-creation can be set-up. In this paper the authors present a template-based design (TBD) approach that supports designers to set-up and explore large design solution spaces. Further, through the combination of CAD systems, a user-friendly application is provided to support design co-creation by involving users in engineering design so as to identify a best solution that provides users with better experiences and satisfactions while being understandable and cut confusions through too many choices and adjustments.

2. Theoretical background

The approach described in this paper belongs to the field of knowledge-based design. Its main goal is the integration of design templates in product structures via a proper mapping. In this chapter a brief overview about relevant subjects, e.g. knowledge-based design, design template, will be given.

2.1. Knowledge-based design

Knowledge-based design is a research area for parametric design that involves complex and iterative processes based on methodologies and technologies for capture and reuse of engineering knowledge. The objective of KBD and its equivalent in product modelling, knowledge-based CAD, is the reduction of time and cost of product development by means of: (1) Automation of repetitive, non-creative design tasks; (2) Support of multidisciplinary design optimization in all phases of the design process. According to La Rocca (2011), the basic architecture of KBD consists of three modules: The requirements such as size, cost, and performance have to be processed using encapsulated knowledge contained in rules, codes, and design tables. Then, the optimal design is returned in form of e.g. drawings or 3D CAD-models (fig.1). Researchers have made lots of efforts in developing solutions in KBD. Various works have been reported, attempting to accommodate different issues in system design and development. While some of the studies introduce general approaches for KBD application development, some present specific case studies (Boyle et al., 2011; Lin et al., 2012).

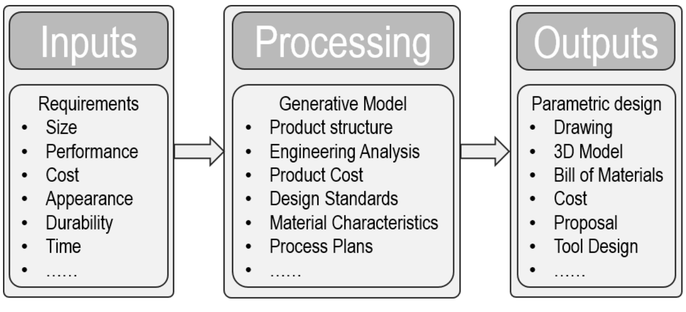

Figure 1. Basic KBD architecture (acc. to La Rocca, 2011)

2.2. Design templates

From a KBD point of view, a design template belongs to automated routines for geometry creation. It may be understood as a parametric, updatable and reusable building block within a digital prototype (Hirz et al., 2013). The product templates focus on product development and can include a variety of design restrictions that supports design co-creation. Product templates can be divided into structure templates, geometry templates and functional templates. Geometry templates are further distinguished into rigid and variable geometry templates. The rigid geometry templates represent library components or carry-over-parts that have additional process parameters available which cover knowledge about application, design interfaces or technical data in general. Variable geometry templates are taken as predefined starting point for embodiment or detailed design that includes all necessary design rules and features (Harrich, 2015). Structural templates address the predefinition of the internal design model arrangement and include e.g. a basic generic product structure and different delimited physical design solution spaces. So, the design process is parallelized in a standardized way. Finally, functional templates in a CAD system represent the implementation of specific problem-solving methods and simulation tools, additionally to the geometry description. When embedded as computer aided engineering environment, a functional template can accelerate the design process since data transfer between design and calculation results is simplified. Other terms for templates are design blue prints, high level features or high level primitives (La Rocca & van Tooren, 2010).

2.3. Design solution space and restrictions

The design solution space can be defined as set of all theoretically possible design solutions for a given problem. With respect to computer-aided engineering, Gero (1990) presented the concept of design prototypes. Following his argumentation, a design prototype represents a space where a design artefact, no matter it is product, subassembly or single part, may be altered in a certain way. The simplest way to do this is changing a product’s parameters and regenerating the design. This special design activity is introduced as *routine design*. In contrast to that, *innovative* and *creative designs* represent the traditional approaches to variant and adaptive design. The limit of creative design also marks the end of the variation possibilities of a given design. Beyond that border only a new design may satisfy the requirements. By this concept, Gero had been postulating design templates as an acknowledged principle of computer aided design, years before parametric CAD-systems became standard in the design departments.
In every design task, the possible solution space is limited by restrictions, e.g. design guidelines (Prieur, 2015) or manufacturing restrictions (Gembarski et al., 2016). These restrictions have to be considered particularly when a design element is created or proceeded to a modification. So, it is important to (1) make the design restriction available during the complete design stage, (2) integrate them directly in the product model and (3) provide this as a design reference for e.g. novice designers. Integrating restrictions in directly in CAD-models offers two major benefits. First, the quality of the designed artefact is verified when all restrictions are satisfied. Second, all necessary design knowledge is stored in one central application which is the CAD-model itself.

3. Template-based design approach

The approach presented here originates from our works to the generative design approach (Sauthoff & Lachmayer, 2014). The basic idea behind is to divide a component into several design elements independently from its assembly structure. These design elements are linked via a skeleton and addressed via multiple levels of parameters (fig. 2). This separation into design elements and the structured parametrization allow the creation of CAD models that are robust against topological changes which is beneficial for computer aided optimization. Together with FEA and a parameter-based optimization, the exploration of the possible solution space may be widely automated. The user defines skeleton and chooses design elements to be included, then defines load application points and load cases and finally determines the degrees-of-freedom of the design. In this context, each of the design elements has to be understood as container for design knowledge and manufacturing restrictions. Precondition is the ability of using KBD-functionalities in the CAD-system.

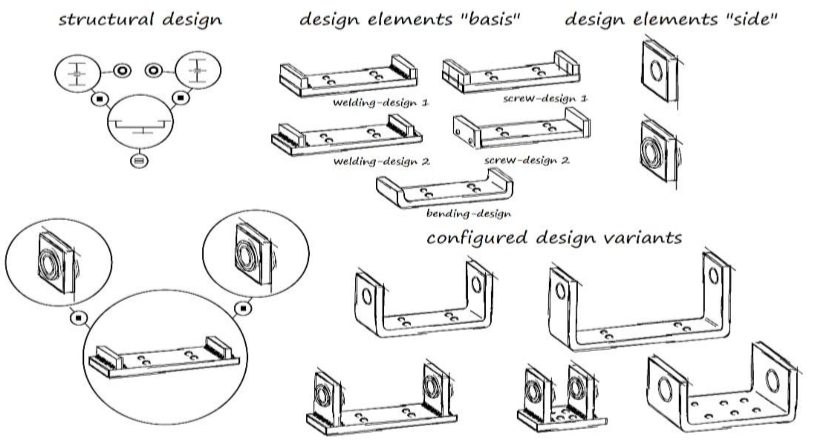

Figure 2. Generative Design Approach for a Mounting Bracket (Sauthoff and Lachmayer 2014)

As basis for co-design, TBD is developed to explore a large design solution space increasing design creativity. The design procedure includes two aspects: design template creation and aggregation of design templates. Here, design templates are created by engineers where the related design knowledge as well as design manufacturing restrictions are implemented in order to setup a large design solution space. As results, the templates aggregation allows either designers or users to configure the desired design templates together to form valid models. So, users who do not possess the relevant knowledge, receive opportunities in designing models as their imagination. In this way, involvement of users as a co-designers plays an important role in realizing design co-creation. In the following section, this two aspects are in detail discussed.

3.1. Knowledge-based template creation

The knowledge-based design template (so called design element) is the essential building block of the TBD approach. Every design element has to capture all of its design intents, e.g. the functional requirements from the customer, i.e. a set of geometric and functional rules which the final product has to satisfy. Normally the design intents are represented by parameters, constraints and design features. A well-structured design element needs to engender a rich set of design possibilities, which not only capture the common design but also the common underlying patterns behind. Through this way, a design template will be able to represent a much wider solution space and so to adapt to new or changed requirements.

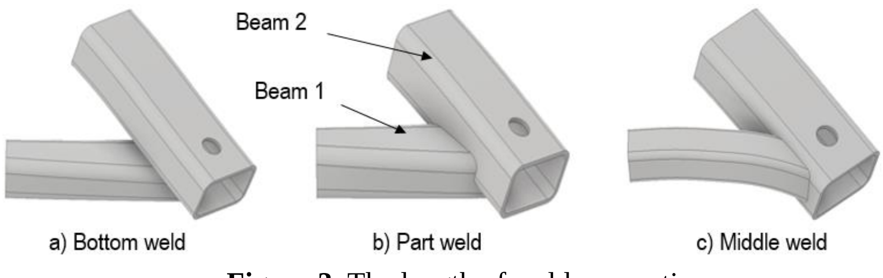

Figure 3. The length of weld connection

The building sequence of a design element plays also an important role in determining its robustness and thus the variability. The basic geometry needs to be structured early and as variable as possible. Less important or configurable features are modelled at latter stages so that the risk of adding references to elements that may be suppressed is minimized. This prevents critical failures due to the less important aspects of the design. Besides geometric properties, the relevant knowledge, e.g. manufacturing restrictions and process information, are integrated into a design template. In this way, the product is described in detail for the purpose to cover the allowable design space. Thus the design element is able to reason about its validity since only configurations with non-violated restrictions are processed. Taking a simple beam joint element as an example (fig. 3), a driving technological parameter is the length of the weld between beam 1 and beam 2 which determines the strength of the joint. In order to reason about the quality of the joint and e.g., safety factors, the later assembled model has to contain information about different load cases and the application points. Depending on this, the design element changes the position and the overlap of the two beams in the butt joint.

3.2. Assembly and configuration of design elements

The aggregation of desired design elements can be realized in different ways. In section 4, we present an automated application that ensures all design interfaces to be linked correctly. The configuration of the single design elements may be accomplished through available in conventional spreadsheet application such as MS Excel, macros or a programmed CAD plug-in. In current CAD system the user can invoke this application in exactly the same manner as any other CAD function. Hence, at the beginning the initial design instance is set tentatively based on the designers' understanding through the application. Regarding to design requirements and design restrictions, different design templates can be selected and adapted to a new design. At any time during this process, the designer may alter the design, add or delete new design elements or modify the selected design element's parameters. Then the generated designs are able to search a large design solution space.

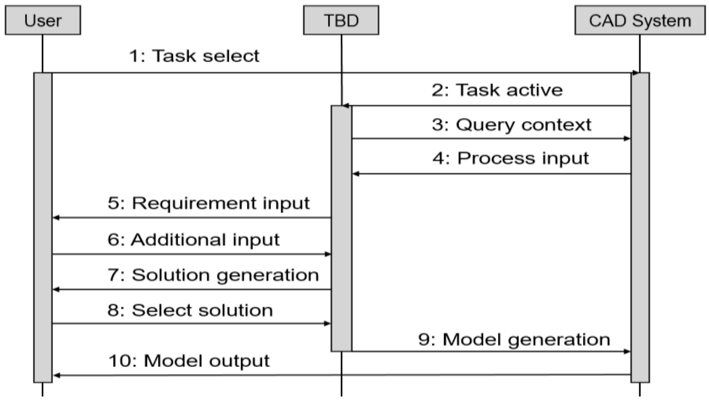

Figure 4. Product configuration process

The configuration procedure as shown in fig. 4, when the user received the design requirements, the design task is identified in a CAD system. According to the requirements, the user transforms them into valid input and invokes the macro or CAD plug-in to process inputs. After design solutions were generated, user has to select the desired solution and gives a feedback to the CAD system. Then the suitable model will be generated. Likewise, random variations by driving design parameters within limits set by modelling structure and the configuration rules are modelled. Through this method, in terms of customer needs, the related design knowledge is already implemented throughout the design processes. Hence, users receive opportunities to configure their desired models as their imaginations which highly increases their satisfaction. Furthermore, the output configuration is not only a design solution, but also a concept that the designer could manipulate, e.g., design element exchange or modification, to search the best solution.

4. TBD implementation: case study

In order to present an overview of the working process that a simplified, yet illustrative, beam structure design as example to demonstrate how the TBD approach applied. For this case study, the CAD-system Autodesk Inventor was adapted and extended by macros. The authors focused on Inventor since it allows the use of multiple KBD-modelling techniques in its out-of-the-box configuration. For a detailed presentation and discussion refer to (Gembarski et al., 2015).

4.1. Template library creation

Following the assumption above, a template library for beam elements has to contain different geometrical configurations (fig. 5). In order to facilitate product variant design, also for e.g.

hydroforming parts, transient beams from one cross section to another are added. Another class of beam elements is butt joints. Basis for this, two or more beams are connected together, e.g., by welding or screwing. The third class is connecting elements to surrounding parts like flanges. Those may also contain interfaces to one or more other beam elements.

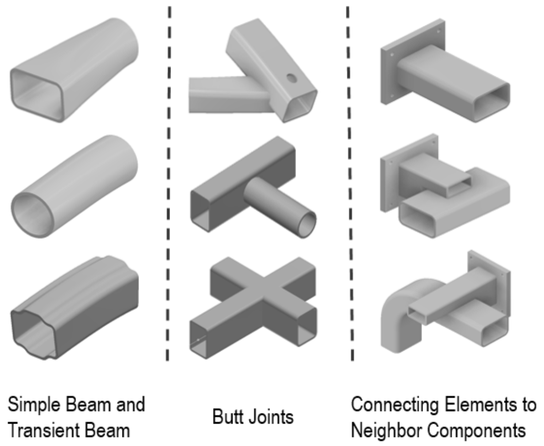

Figure 5. Design Elements for Beams

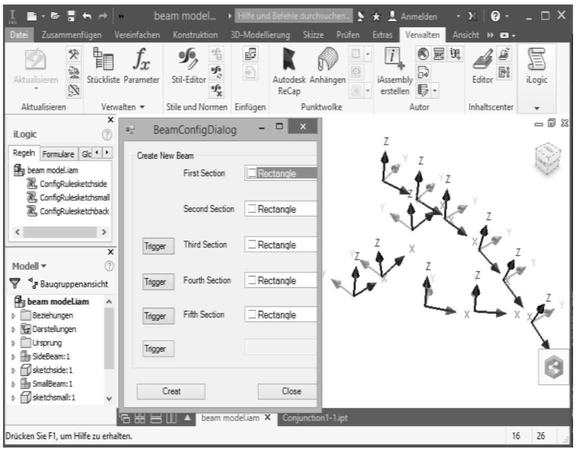

Figure 6. Skeletal Design

4.2. Beam structure generation

All these design elements may be assembled together via a skeletal design consisting of several local coordinate systems with six spatial degrees-of-freedom each that are constrained by parameters. In order to achieve a user friendly dialog, a CAD plug-in application has been implemented into Inventor that supports the generation of such beam frames. In Inventor the user can invoke the application in the same manner as any other CAD function. It provides user operation dialogs for creating the initial skeletal design (fig. 6), position and orient the connection points, selecting the required design elements and change parameters in all levels of the model hierarchy.

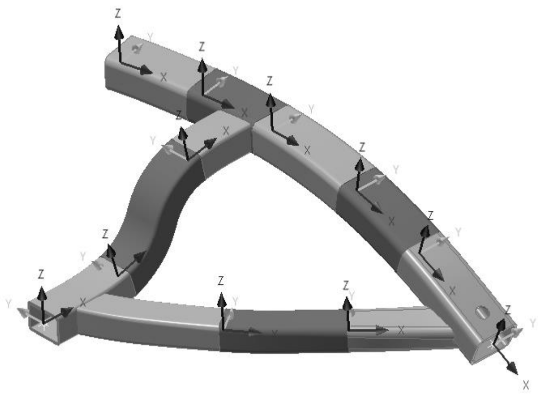

Figure 7. Intelligent template of a beam frame

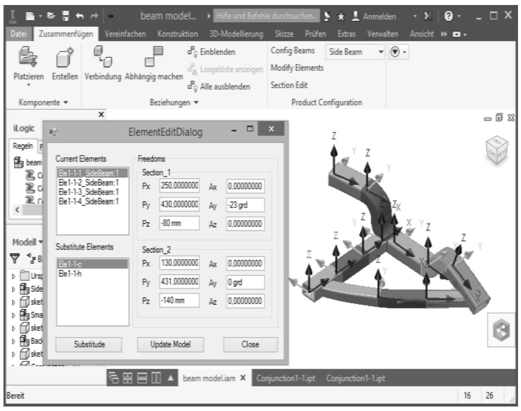

Figure 8. Connecting point modification

The interface profiles administer the shape of the cross-section. In order to do so, each of the design elements has an identifying parameter for all of its cross-sections. Based on the cross-section, the required design elements were reasoned and selected. Then all selected elements have to be placed at the right place according to the assembly structure which is basically done by inheriting parameters of the assembly structure to the design elements. On the one hand, the center points of the local coordinate systems function as positioning aids for placing one element after another. On the other hand, the orientations of design elements couples in the modelling structure link the orientation of the intersecting faces to different design elements in accordance with the local coordinate systems. Then a beam frame was generated by an Inventor application according to the assembly structure (fig. 7). By changing the section interface profile that different models will be generated.

4.3. Beam structure detailed design

By the time, a strategically developed knowledge-based design template library was established. The design problem is represented as a constrained parametric search problem, where design solution space is explored based on the modelling structure, assembly structure and template library throughout the design development process. So the task to explore the desired design solution is transformed to modify the generated models above. The implemented CAD plug-in application provides a user interface for this operation. This interface gives the designer/user opportunities to innovate. According to available (production) technologies, the designer defines the boundaries like the skeleton and the parameter value ranges (fig. 8) and lets the computer find out the best solution.

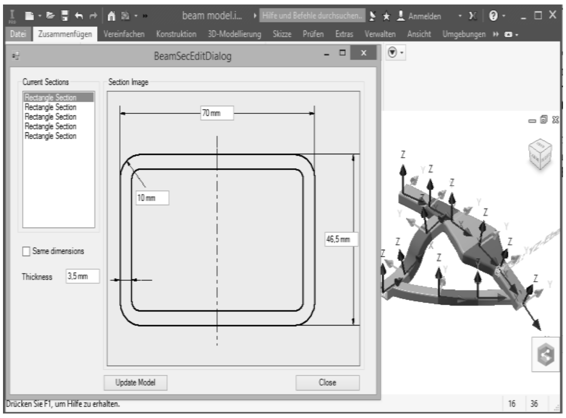

Figure 9. Cross-section modification

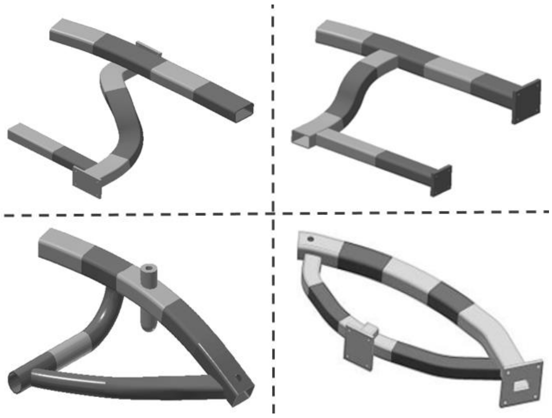

Figure 10. Beam structure variants

Moreover, the same plug-in allows changing the cross-section of the single beam elements. This addresses not only the shape but also the corresponding parameters. In case of the rectangle tube this is width, height, fillet and wall thickness (fig. 9). If a cross-section is e.g. switched from rectangular to round tube, the corresponding design elements and parameters are substituted. The old parameters are stored for later retrieval. Fig. 10 shows different configurations of beam structures.

4. Discussion

Design problems in TBD are transformed to a configuration problem of multiple design templates. The implementation of design knowledge allows either designer or user to generate valid product variants in terms of the design templates which increases the design efficiency. In this way, design creativity is enhanced as well by involvement of users because some solutions are generated which the designer may not have imagined or created. Furthermore, integrating manufacturing restrictions as part of the generative design process, saves the designer’s time otherwise lost iterative changes typical of a traditional design process. Another advantage is this approach provided a design guidance to create a design solution for the user who may not possess the relevant knowledge. The potential of customers as active contributors in product development is a major aspect for co-creation.
The approach also is an iterative design strategy increasing design creativity. At the beginning of the design process when not all requirements are fully determined, the TBD can be carried out with concept models as well. On receiving these initial results, designers will usually study the various design restrictions and the overall design properties to refine the problem. Once the candidate solutions are identified, the restriction’s ranges can be re-defined with much better accuracy.

5. Conclusions and outlook

The presented approach offers possibilities to explore multiple alternatives between problem space and solution space. Through the use of the template library, a large number of design variants can be investigated in the same time it might take to create one design using a more traditional approach. In this way, the application of template-based design for the generation of parametric associative concept geometries supports a user-friendly definition of flexible design co-creation. At last, based on the

automated functionality, a large number of topological variants can be created with relatively little manpower by involving users in engineering design. The ability to include optimization strategies based on FEA and parameter-based optimization, widely automates the solution space exploration.
Future research in the development of the TBD approach is the test of reasoning techniques. Different reasoning methods have to be identified that either the integrated design restrictions or different design templates can be easily retrieved. Corresponding optimization strategies have to be synthesized in order to carry out the automated exploration of the solution space fast and effective. Another important point will concentrate on the development of methods and tools for a further integration of design templates. The development of a modelling structure integrating design knowledge and manufacturing restrictions has to be enhanced.

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