Generative Design Approach for Modelling of Large Design Spaces

Bastian Sauthoff and Roland Lachmayer

Abstract Mass customisation of mechanical and mechatronic products requires computer-aided configuration tools including parametric models of the product. For an extended individual adaption, approaches including iterative configuration processes are necessary. Knowledge-based engineering systems (KBES) are developed for this kind of customisation tasks among other things, but they are still not universally applicable and accepted in the industry. Thus, in this paper, an approach for the modelling of large design spaces by parametric models is presented. This approach implies a confinement of the widely defined pretension of KBES by a systematic modelling of practical conversant design solutions. In contrast to the modelling of higher-level design rules, the exclusion of inexpedient variants is completely possible. The detailed aspects of the approach consisting of a structural design, effective areas and design elements are illustrated in this paper as well as methodological aspects. The application is demonstrated by a wheel carrier design.

Keywords Product modelling · Parametric design · Design optimisation · Knowledge-based engineering · Modelling principles

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1 Introduction

For mass customisation of mechanical and mechatronic products, computer-aided configuration tools are common used in the industry. Based on a static and a customer-dependent set of functional and geometrical parameters, the final design of a product is configured. The precondition for the development of such kind of configuration tool is an explicit relationship between function and design. While the approaches of size ranges and assembly design kits, e.g., the methodology of Pahl et al. [1], are predicated on this aspect, extended configuration demands and iterative adaption process. This aspect is illustrated in Fig. 1.

Every product is defined by a set of parameters subdivided in geometrical and physical ones. A fraction of this parameter set is accounted for configuration. The functional design is generally modelled by interrelationships of parameters. If a set of explicit constraints is deducible from the interrelationship including all configurable parameters, a direct configuration is feasible. Whenever an explicit constraint set cannot be defined, an iterative configuration process has to be established. In this case, the well-adapted parameter configuration cannot be calculated directly. An evaluation of a specific parameter set by an analysis model combined with an iterative parameter variation is the only feasible way. Particularly for the configuration of components dimensioned by physical field problems, an iterative configuration is essential. Thus, an iterative configuration is obviously much more complex that a direct configuration, but the feasibility of configuration is more flexible as well.

To support mass customisation based on iterative configuration models, knowledge-based engineering systems (KBES) have been developed since the 1980s. The exploration of large parts of the design space as well as the automatisation of repetitive design tasks is still the visions of this research field. But the complexity in reference to development and implementation as well as the integration in company working processes restrains the application today as well [2, 3].

1.1 Challenges of Extended Configuration

To confine the approaches of KBE in consideration of application for mass customisation, the today's challenges of this field are summarised.

1.1.1 Effort of Development

Normally the product design grows up continually during the design process. Thus a KBE-based configuration systems must include the steps of the underlying design synthesis. The design steps have to be transformed into rules including

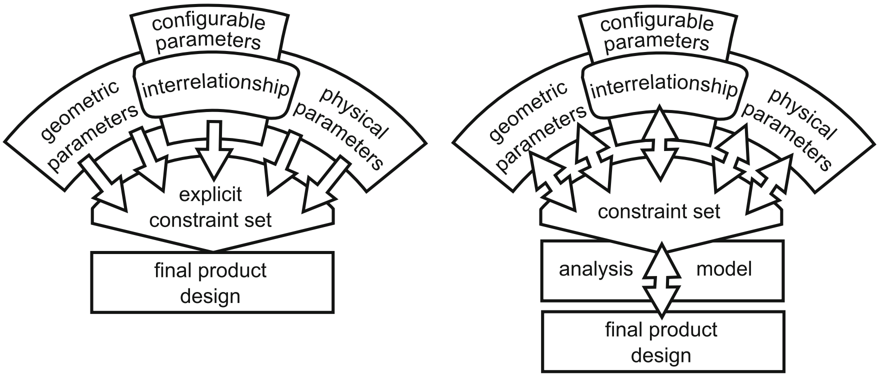


Fig. 1 Direct and iterative configuration

functional as well as geometrical aspects on an abstract level. This way of engineering fundamentally differs from the iterative and creative way of engineering work. Additionally, the development of such a meta-model efforts a lot of engineering resources which can only be applied by big companies. Thus, major challenges relating to configuration tools in almost the same manner are an improvement of accessibility by engineers and methodology for applicable development [2].

1.1.2 Implementation and Interaction with Existing Tools

A lot of scientific articles can be found about specific implementations of KBES characterised by specific programming languages to build a configuration system. Until now a lot of CAD tools are quite familiar with parametric modelling and direct configuration features. But tools for a development of iterative configuration tools often require deeper understanding of programming. Additionally, the programming and connecting interfaces, especially between tools of different companies, are difficult to manage. Thus, implementation of iterative configuration tools in existing development tools as well as existing work flows without isolated application is quite a challenge [3, 4].

1.1.3 Integration of Product-Specific Knowledge and Design Rules

Analysing guidelines for engineering design, there are two different kinds: On the one hand, general design rules are describing engineering knowledge which is related to a specific manufacturing technology of principles of mechanics. These rules are important for the design work of engineers, but a transformation into constraint-based rules of a KBES is quite difficult. One reason for this aspect is the independent formulation of product-specific geometrical design. On the other hand, there are a lot of product- and company-specific design rules based on engineering experience, simulation, or testing. These are often closely solution oriented and not commonly available. Because of this aspect, an integration in a configuration system is only possible if the design space is very close to the application range of these rules. Thus, the formulation of design rules on an applicable but also product-variant-space level is still a challenge [1, 5, 6].

1.1.4 Exclusion of Inexpedient Variants While Modelling a Large Design Space

Exploring the design space of variants for a defined configuration parameter set the ratio of theoretical available, but inapplicable design solutions is important for the configuration effort. Particularly this aspect is weightily if the design space increases. Thus, a modelling of the complete design space is often inefficient. A defined restriction of the design space to the sections where feasible solutions are expected is quite a challenge.

Summarised a confinement of the approaches for KBE with focus to mass customisation is a necessity to make the grade of these challenges. In particular, available geometric-related design solutions have to be brought in focus instead of an overlaying meta-model describing design activities in general.

2 Parametric Modelling Approach

Based on this perception, an approach is developed focusing the exploration of large design spaces by well-known design concepts.

2.1 Levels of Design Impact

For identification of a feasible level of abstraction of a product design, the different levels of design impact are analysed. In Fig. 2, the levels of design activities related to the development steps are illustrated. The iterative design process is often affected by the following developing strategy: Planning activities as well as first conceptional developments are made on general product level. During the ongoing design process, the activities are further more focused to component design and eventually to component section details. Thus, the impact of design switches into detail. But the final product design is defined by an iterative reflection of the design increasing the point of view to the product level [7].

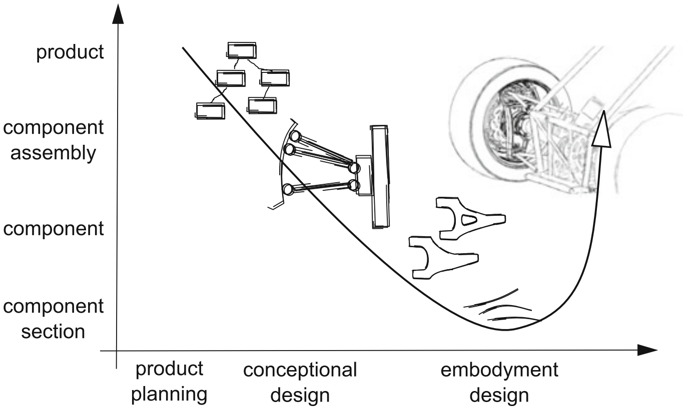


Fig. 2 Levels of design impact instancing a wheel suspension

For mass customisation using KBE-based tool, this aspect clarifies the problem of modelling underlying design activities. Both directions of abstraction have to be integrated.

2.2 Modelling Approach

Because of mentioned aspects, it is a reasonable way to develop an approach which is strongly related to the design of a product itself. For this purpose, different methodology approaches of embodiment design are analysed. The design methodology of Roth [8] is identified as a very strictly structured approach nearby the geometric forming of design. Roth subdivides the process of embodiment design in the steps of structural design and contour design. The inherent structure of component or component assembly is designed using structural design. Based on this minimal-function-oriented skeleton, the contour is defined. During both steps, an iterative process of shape variation is done to identify the best design. The interaction of components is modelled by effective areas. The basis of all steps and operations is scalable representation of the product.

Based on this approach, it is recommended to apply this way of geometric oriented design for the development of computer-aided configuration models. Because of the issue that a defined component-oriented structure with effective areas to link the structure elements limits the variation part boundaries, the approach is expanded to a design-characteristic-oriented structural design. This implies that effective areas are not solely located at the boundary of parts. Based on this a product is represented by inherent sections of structural elements coupled by effective areas. For the variation in the final shape, so-called design elements are defined which are related to a special constellation of structure and effective areas. Thereby, the topology as well as the contour design of an design element

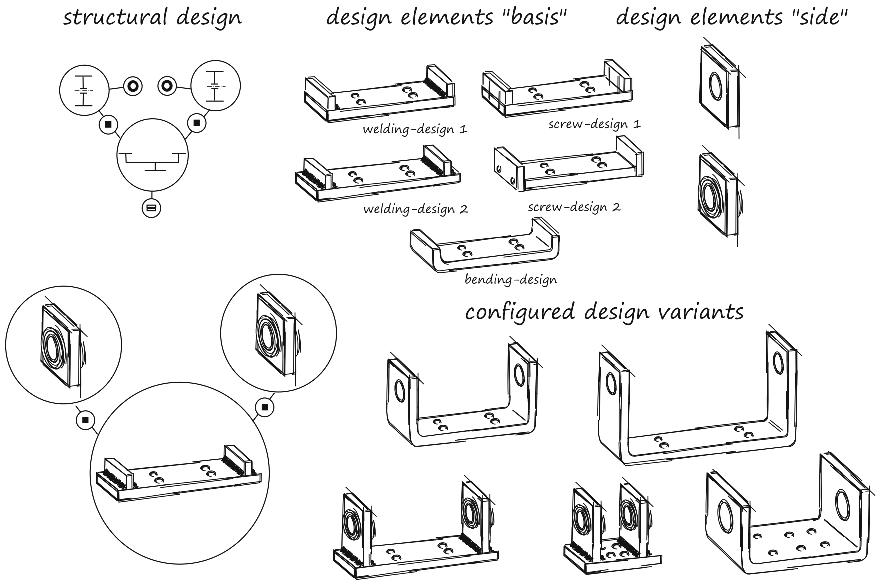
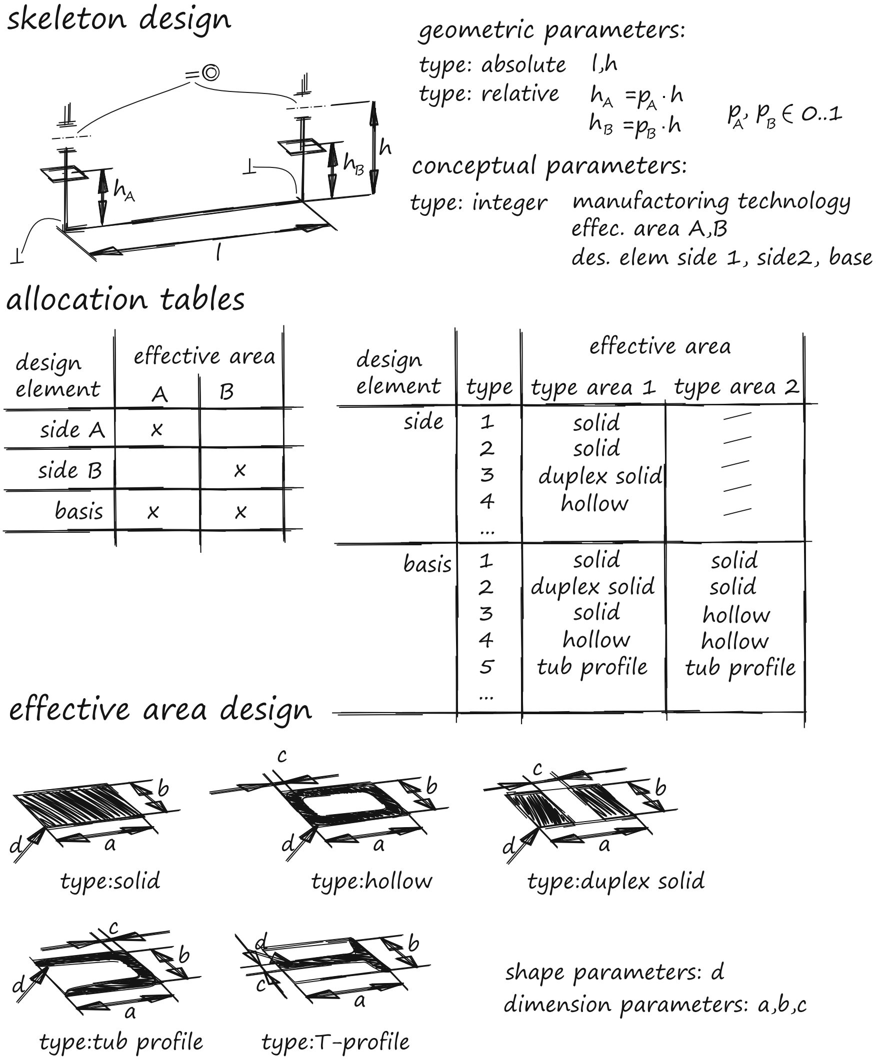


Fig. 3 Modelling approach instancing a mount

can vary completely while retaining the inherent structure. In Fig. 3, the approach is illustrated by a mount. The inherent structural design of a mount consists of a base element with one effective area for linking to a further component and two internal effective areas for linking to design elements of the side class. The side class elements are identified as characteristically equal. They have an external effective area for circular formed components. For the design elements of the basis class as well as the side class, different design variants are developed considering several design rules and manufacturing technologies. Based on the parameters of the structural design and the effective area design, the elements are assembled to different design variants.

2.3 Levels of Parametrisation

Going into detail different levels of parametrisation are identified. On the one hand, there are a few fundamental parameters on the level of structural design characterising the whole mount. On the other hand, there are special parameters characterising the individual design of the effective areas subordinated by the design element shape. Thus, the parametrisation is classified by these three levels. In Fig. 4, the two levels of structural and effective area design are illustrated for the mount. On the level of structural design, the length and the height are the fundamental parameters. Additionally, the positions of the effective areas related



design element	effective area A	effective area B
side A	x	
side B		x
basis	x	x

design element	type	effective area type area 1	effective area type area 2
side	1	solid	—
	2	solid	—
	3	duplex solid	—
	4	hollow	—
	...		
basis	1	solid	solid
	2	duplex solid	solid
	3	solid	hollow
	4	hollow	hollow
	5	tub profile	tub profile
	...		

Fig. 4 Design of skeleton and effective areas

to the skeleton design are parameterised to complete the geometric model. They are, different from length and height, defined as relative proportion parameters supporting the variation independence. To control the substitution of effective areas and design elements, there are additional conceptional parameters on the level of structural design allocating the variants by integer parameters. Furthermore, a parameter for the manufacturing technology is defined which constrains unfeasible combinations of design elements assigned to different manufacturing technologies. Additionally, constraints for the combination of design elements and effective areas are necessary because the type of an effective area is fundamentally important for the shape and topology of the design elements. Thus, allocation tables are introduced to classify the design elements by including effective areas and the design element classes by effective area design. Thereby, the design space is restricted to feasible design solutions. The allocation tables are established on the level of structural design, too.

The effective area designs of the mount, illustrated in Fig. 4, are parameterised by a shared set of parameters. These parameters are interpreted individually by every type of effective area. Width (a) and length (b) of the area designs are identified as characteristic dimensions completed by a parameter for the inner proportion (d). While width and length are nearly identical interpreted by every area the parameter c, defined by a fraction of width or length, has fundamentally different influence to the different area designs. Nevertheless, a value variation in c in the range of 0.1 is accomplishable without the risk to generate unfeasible design variants. Thus, this generative approach demonstrates a combination of a large design space and the confinement of feasible solutions. The parametrisation of design elements is implemented by the same strategy.

3 Modelling Principles for Generative Design Approach

Based on experience in modelling different types of design elements according to the above approach, general modelling principles are formulated in order to support its application.

Modelling principle 1 *Level of parametrisation: The impact of a parameter variation should be confined only to one level of structural design, effective area design or to a type of design elements. The impact should be as local as possible.*

Modelling principle 2 *Complexity of design elements: For topology variations, the definition of additional design elements is advisable, while contour variations are feasible modelled by one design element as long as the order of the contour design does not change.*

Modelling principle 3 *Coupling of parameters: Coupling of parameters in the space of one level should be avoided. Coupling of parameters over different levels is preferred.*

Modelling principle 4 *Parameter properties: For a stable regeneration of the design model, parameters should be coupled by fractions of other parameters in a specified range.*

Modelling principle 5 *Parameter hierarchy: The level of structural design should be dominated by a small number of parameters. The number of parameters of the effective areas as well as the design elements should be decreased to a suitable level by linking similar parameters. Example: The curving of different* *edges should be described by one parameter as long as a curving does not fundamentally characterise the design element.*

Modelling principle 6 *Design rules: Design rules should be applied to each effective area design as well as to each design element individually. The definition should be as independent as possible from the value range of parameters.*

Modelling principle 7 *Choice of CAD elements: The used CAD elements like lines and arcs to model the design elements should be as simple as possible to support a robust parametrisation. In particular, higher-order elements like splines are dependent on several dependent parameters. For example, the modelling of a curved contour by one line and two arcs instead of a spline limits the design space but improves the parametrisation.*

To demonstrate the application of the approach, the design space of a race car wheel carrier is exemplified. The impact for application is the scope of individual adaption of the wheel carrier to its load cases [9].

4 Application Example: Wheel Carrier

A wheel carrier of a race car (Fig. 5) consists of a segment for the wheel bearings and three application points for the steering tie rod and the suspension arms linking the wheel to the body. Directing the wheel forces to the application points is the main function. Thus, the design of the wheel carrier is significant for its durability as well as its weight and manufacturing costs. The structure of the carrier is analysed, and three inherent types of design elements are identified: The bearing element which includes the wheel bearings, three connector elements linking application points and bearing element and three application point elements including the connection to the arms and the rod. Although the connector elements as well as the application point elements differ in their local occurrence, they are merged in one element class for every element type. The effective areas between bearing element and connector elements are identified as cylindrical faces, the other effective areas are plains with different contour types. The skeleton for the parametrisation of the structural design mainly consists of effective area positioning parameters. The distance between the application points and the bearings is inherent parameters for the wheel carrier, too. In Fig. 5, exemplary a choice of connector design elements is presented. Although there are different manufacturing variants (casting, welding, and cutting), every instance is modelled by an identical parameter set. The determining parameters for these elements are the wall thickness, edge rounding, and properties of the right and left contour.

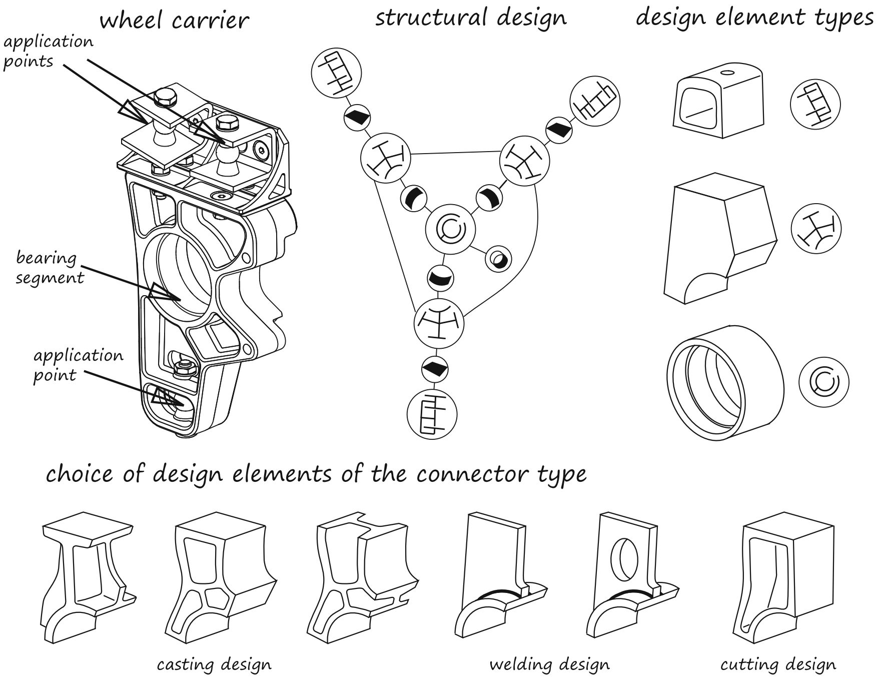


Fig. 5 Generative design model of a wheel carrier

4.1 Design Adaption by Optimisation Algorithm

The optimal design of the wheel carrier is calculated by an optimisation algorithm based on an objective function including the mechanical stress distribution, the manufacturing costs as well as the weight of the carrier. Modelling the design space of the wheel carrier by the presented modelling approach, all design variants can be generated by parameter variations. Thus, optimisation by a genetic algorithm is a feasible way although the design model includes topology design changes. For the implementation of the generative design approach, a computer-aided design tool which support parametric design in parts and assemblies is necessary. Additionally, the tool has to provide an application programming interface to implement the allocation tables controlling the variation process of effective areas and design elements. Based on these features, an optimisation can be done manually. For the adaption by a genetic algorithm, the implementation of an interface to a finite element environment as well as an external genetic algorithm is implemented [10]. This requires definitely some effort but is a more feasible option than developing an standalone knowledge-based engineering system.

5 Conclusions

The presented generative design approach supports direct as well as iterative configuration as a tool of mass customisation. The design space is confined by systematic analysis of structure and shape. On the one hand, feasible solutions are favoured, and on the other hand, this way of modelling limits the number of solutions in general. No higher-order design rules are formulated whereby the complicity is reduced. The integration of all design rules in the design elements does not require such a formulation. Relating to mass customisation, this approach supports the computational modelling of individual product variants focusing embodiment design. In comparison with common KBE applications, creativity and the iterative design exploration characterising the way of engineering work are not decreased. But for an implementation of an optimisation process, programming effort is still required. Outlining further challenges, an extension to assembly design introducing part overall effective areas is necessary. Further there is the question of the number of design elements necessary to model a product optimally.

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