Title:
Function Model Based Generation of CAD Model Variants

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Introduction:
The goal of product development is to generate an artifact that fulfills a certain set of functions which generate value for its users and other stakeholders [5]. In this, to express what a product is to do, i.e. its *function*, is the most important task of a designer [6].

However, the most common models used in product development are computer CAD models, which represent only the results of the product development process - the geometrical form of the product. While these geometrical models lack a representation of function and design rationale (DR), they are needed as the basis for the analysis of a product design's performance and manufacturing.

Since the performance of a design can only be analyzed *after* its geometry has been created, designers aim to generate a set of alternative design concepts in order to be able to choose the one performing best. This approach is described as design space exploration (DSE) [9] - discovering the concept which fulfills the required functions best. To be able to explore the design space effectively, that is generating multiple variants of a concept and analyzing to find the best possible configuration, different technologies generating variant CAD models have been developed. However, while certain technologies such as knowledge-based engineering (KBE) or design automation (DA) allow for major geometrical variation, CAD models are still considered to be too rigid for the introduction of new solutions and designs [3] since they "are made for drawing, not design" [9].

While "Design to function" is well addressed in design theory-based literature, no support exists to generate the related geometrical models [8] – which in turn are needed for analysis. Most approaches place functional design in advance of "embodiment design", where the geometrical product representations are defined [7].

The combination of lack of function representation and rigidity of modelling in CAD leaves large sections of the design space unexplored. As a result of this, potentially higher performing variant designs are neglected and radical innovation may be stymied.

This results in the challenge to combine the representation of DR and expected functionality with the geometric representations of CAD models. This challenge has also been presented in literature, e.g. [8, 9]. To close this gap, in this publication, an approach coupling function models with CAD models is presented. Where in earlier works this connection has been described theoretically [2, 4] or performed manually [1], the approach presented here provides an automated generation of CAD models based on the alternatives in a function model. It introduces a linking mechanism between the functional and geometric domain, as well as an assembly algorithm for CAD models based on the DR represented in a function model.

The approach is demonstrated on an example from an industrial case study, a turbine rear structure (TRS). Alternative sub-solutions are generated in the functional and geometrical domain, and the approach is evaluated in terms of effort to generate CAD models of alternative designs.

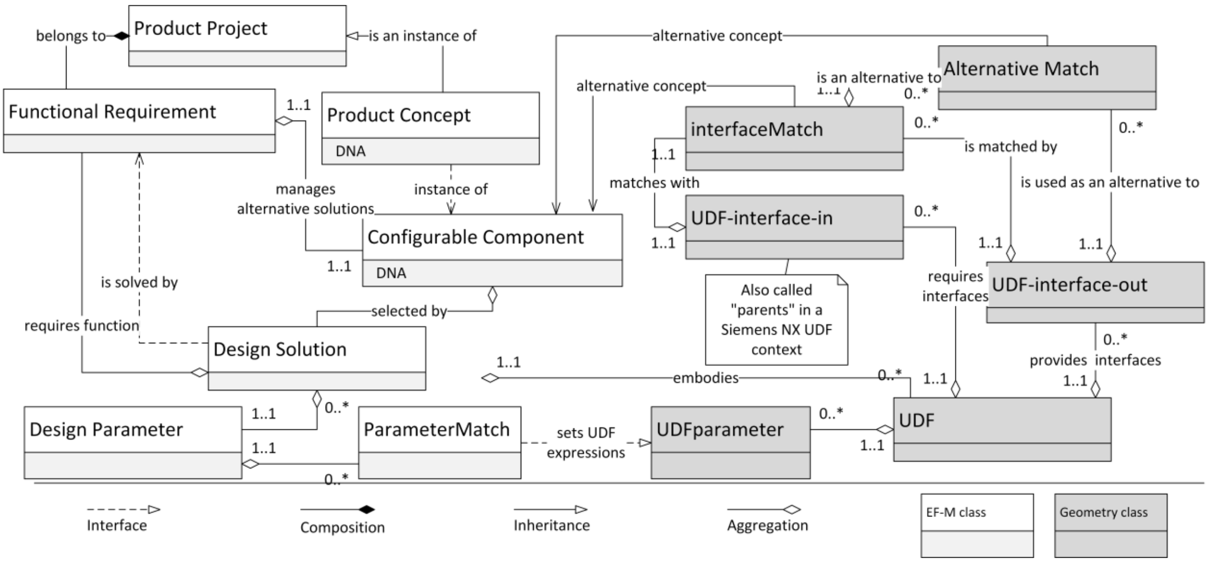

Fig. 1: UML class model of the OMFG behind the DA approach. Classes in white describes the objects necessary to represent a EF-M model, while classes in grey represent the DA related classes.

Proposed approach

The proposed object model for function and geometry (OMFG) uses enhanced function-means (EF-M) modelling as function modelling (FM) method. In an EF-M model a product's DR is modelled through alternating between functional requirement (FR) and the respectively solving design solution (DS), and subsequently required sub-FR [2]. The modelling approach allows to introduce alternative DS for each FR, thereby enabling the introduction of novel ideas into an existing product model. Alternative design options, be they of modular or dimensional variety, are captured in configurable components (CC) [2].

The approach builds on the availability of an existing CAD model, the "legacy model". If not performed before, the geometry is decomposed into a function model representing the design rationale of the CAD model. This process is performed by product experts who are aware of the design intent. A detailed description of functional decomposition of an existing product into an EF-M model can be found in [1].

Based on this structure, the legacy geometry model is decomposed into user defined features (UDF), which are then associated with their respective DS in the EF-M model. This association, together with all information about the UDF, their interfaces, expressions (as design parameters are called in Siemens NX) and relations are stored in a proprietary object model based on the CC framework, which is illustrated in Figure 1. Novel solutions for existing FR are developed together with their sub-functions and sub-DS, and geometry for each new solution is created. The instantiation algorithm generates all combinatorial concepts based on the EF-M model, and an assembly algorithm generates the respective geometric models in CAD. The assembly algorithm is based on the parameters and interfaces of DS, and their respective UDF, as stored in the database.

Using the instantiation of EF-M, the combinatorically resulting concepts from all sub-DS can be created. This capture of multiple alternative sub-solutions and the resulting variant concepts is the basis for the DSE ability of the presented approach.

The FM part, illustrated in unified modelling language (UML) model in Figure 1 on the left-hand side, of the OMFG is coupled to a modularized CAD model, on the right hand side in Figure 1. The basis for the modularization is the UDF object which can be found in several CAD frameworks. The geometry is decomposed into UDF based on the DR in the EF-M model. Each DS is associated to a set (none in case of a non-geometrical solution) of UDF which represent the geometry which embodies the design.

The OMFG captures the interfaces required for the assembly of the UDF. Based on the existing network of UDF interfaces, newly introduced DS and their respective geometry can be mapped towards existing interfaces. This *AlternativeMatch* object enables a reconstruction of the entire concept's geometry even if an alternative DS, and therefore alternative geometric elements, are used. It also reduces the number of necessary mapping operations when a new DS's geometry is introduced.

As a result, design alternatives captured as DS with associated UDF in the OMFG lead directly to CAD models of new concepts. To do so, first the function model is instantiated, generating individual concepts by combining all sub-solutions in all possible combinations. This instantiation generates a "DNA" for each concept, listing each FR-DS combination and making the concept unique.

Based on this DNA, the instantiation is performed in the geometrical domain, making use that each DS is associated with its respective embodiment in the form of a UDF. The assembly algorithm selects all UDF associated to the DS in a specific concept, and reads their configuration rules in the form of *interfaceMatch* and *AlternativeMatch* objects. The configuration rules are individual for each product concept, since they rely on the individual combination of DS, UDF and parameters, as created by the instantiation algorithm. All UDF are placed into a new part file for each concept. For this, the assembly algorithm sorts the UDF based on interface requirements, independent of the order of DS they are associated with. Lastly, each part-file is saved and linked to the respective concept. Each instance is directly coupled to its respective design rationale in the function model. Product behavior data can now be simulated in the geometry model and be associated with the product instance, allowing for a fact-based evaluation of the different concepts and supporting decisions for further development. Since the concept's geometry model is assembled on demand, changes made on individual DS parameters or geometries can be performed independently, and the assembly is then repeated.

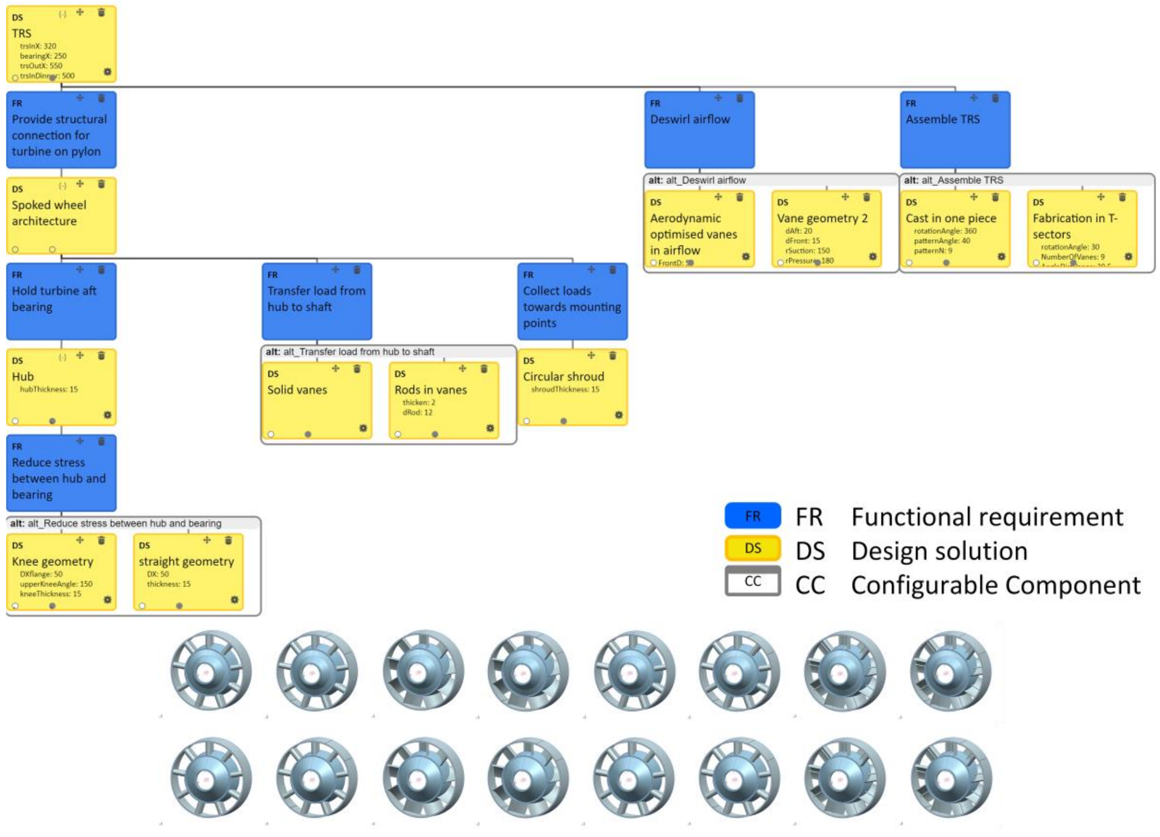

Fig. 2: EF-M model including alternative DS for most FR, and CAD models of all 16 instances of the alternative solutions for the TRS.

Demonstration of approach on an engineering design case:

The OMFG is demonstrated exploring alternative designs of a TRS, a static element of a turbofan engine. An existing CAD model is decomposed into an EF-M model. Based on the identified sub-solutions in this model, new DS are introduced for different FR. The entire EF-M model, including the four new DS, is shown at the top of Figure 2.

In a next step, the four new DS have been embodied as UDF and mapped into the OMFG. With the instantiation algorithm of EF-M, 4^2 =16 different concepts are created. Using the mapped relations in the OMFG, CAD models of all 15 new and one legacy concept are generated automatically. The CAD models of the 16 instances are shown at the bottom of Figure 2. Each instance is composed of an individual set of geometrical solutions.

To illustrate the efficiency of the presented approach in terms of DSE, it is compared to the manual effort that would have been necessary to model the same number of concepts. Based on this, the efficiency of the approach for products with more alternative DS on more FR is interpolated. The efficiency is measured in "effort" or "interactions", where one interaction equals a selection in a user interface or the entering of a value into a mask.

Using this estimated effort, the presented approach pays off relatively quickly. Figure 3 shows that already for three or more FR which have two alternative DS, the OMFG approach takes less effort to generate all possible combinatorial concepts than a manual modelling would. Computations with penalty values for setup of the OMFG and/or integration of UDF into the module have shown the same trend, albeit a trade-off in effort for higher numbers of FR with alternative DS.

These measures indicate that the DA approach of OMFG, where geometry is generated in a functionally driven way, and alternative concepts is efficient than a manual modeling using parametric design. This can contribute to faster, more systematic and more efficient DSE approaches.

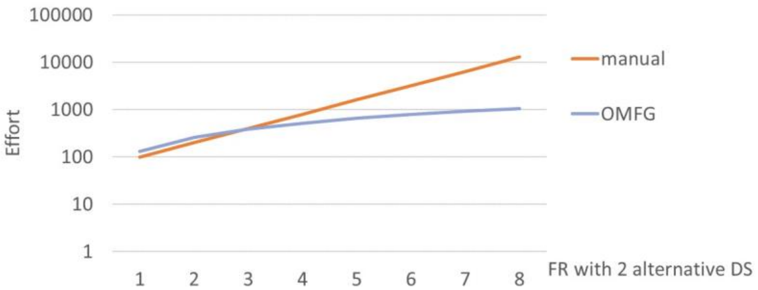

Fig. 3: Effort to generate all possible combinatorial concepts, depending on how many FR have 2 alternative DS.

Discussion:

The presented OMFG approach for the generation of alternative product concepts based on alternative sub-solutions has shown to deliver variant CAD models based on a concepts represented in a function model. As such, it contributes to the closure of the gap between models of different abstraction levels, as described in literature and observed in industry. The generation of variants of a CAD model contributes to DSE, while it extends the focus beyond the generation of geometry model into the functional domain.

The approach builds on the assumption that each geometrical element in a product has an identifiable function. Only based on this assumption, the total functional decomposition, a core step in the presented approach, is possible. While earlier work [1] has shown that this is feasible on single products, it is a point of an ongoing discussion and further research.

The core of the DA partition of the OMFG is the management of interfaces between UDF, which enables the exchange of alternative DS and their geometry. While having been verified on a relatively simple product derived from a case study, the complexity of a larger product might bring so far unencountered challenges such as disappearing interfaces, exceeding parameter ranges or circular relations.

The OMFG approach for DSE is capable to produce CAD models for all concepts of a full combinatorial of all sub-solutions. The vast growing number of these sub-solutions, and the effortgains in generating all of these geometry models is one of the main arguments for the presented approach. However, beyond arguments of scalability, a too large number of CAD models raises challenges in terms of analysis resources downstream. To encounter this, the product information captured in the OMFG can be used to already down-select the number of prospects for the subsequent design process. A first step towards this would be the implementation of the *constraint* (C) object as found in the EF-M theory [2]. A DSE process relying on selection in the functional domain has been described by [4].

Conclusions:

An approach to automatically generate CAD models based on the alternative solutions captured in a function model has been presented. This can enable faster, more efficient and more methodical DSE than the use of either only CAD models, only function models or unconnected models in both domains. The applicability of the effort has been shown on an example derived from industry, and the efficiency of the approach has been explored theoretically based on extrapolations from the case sample.

While this shows that the approach theoretically works to support DSE, and that scalability of the approach is attractive, the next step is to validate the method on realistically complex geometries of aero engine components.

The approach stands out towards other DA solutions in that it combines the generation of geometric models with an individual design rationale for each concept. Through this, it can give more control to the designer in both the modular as well as parametric bandwidth. Compared to FM approaches for DSE, the presented one enhances the available approaches by actually implementing the CC theory and thereby enhancing the function model with both geometry and the possibility for further product behavior analysis.

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