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CONNECTING FUNCTIONAL AND GEOMETRICAL REPRESENTATIONS TO SUPPORT THE EVALUATION OF DESIGN ALTERNATIVES FOR AEROSPACE COMPONENTS

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ABSTRACT

Novel product concepts are often down-selected in favour of the incremental development of available designs. This can be attributed to the fact that for the development of a new product, simulations and analysis based on high-fidelity CAD models are required, which are expensive to create. To solve this problem, the use of a function model (FM) as intermediate step between ideation and embodiment is suggested.

The approach has been examined in a case study with an aerospace company for the development of a turbine rear assembly, using multiple workshops and interviews with practitioners from the company.

A multitude of novel solutions, even extending the functionality of the legacy design, were captured. The FM approach proved to support the representation, analysis, and configuration of 102 different concepts. Although supported by the FM model, the embodiment still showed to be a bottle neck for further development. The subsequent interviews with practitioners showed that the benefits of the approach were seen, but experienced as too complex.

Further work will concern a more systematic connection between the FM and CAD model, in order to automate of the embodiment process.

Keywords: Functional modelling, Design engineering, Product modelling / models, Computer Aided Design (CAD)

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1 INTRODUCTION

Among the main drivers for successful product development of safety critical and complex products – such as in the aerospace industry – are reliability and performance. As a consequence of the need for reliability, new products in this industry are commonly developed incrementally (Wyatt, Eckert and Clarkson, 2009), where existing products are gradually refined and adapted. Radically novel solutions, although they may enable leaps in performance (Lawson and Samson, 2001), are often abandoned in very early stages of development since there is not enough knowledge available about their behaviour. Usually, the risk of developing novel solutions over incremental solutions is perceived as too high.

Knowledge – and thus the ability to reduce uncertainty and therefore risk – is commonly generated through either physical testing of components or virtual simulation and analysis of product models (Thomke, 2001). In engineering product development, the basis for such simulations – such as for aerodynamics or structural integrity using the finite element method (FEM) – often require high-fidelity CAD models as the core input (Eckert *et al.*, 2017). However, the creation and variation of high-fidelity CAD models is expensive and time consuming. This is especially true when introducing new solutions or functionality into highly integrated products, where the CAD models bear an extended complexity. As a result of this, the exploration of a wide range of alternative designs in the geometric domain is often neglected.

As the main problem in this process have been identified the challenges related to creating high-fidelity geometry models (in the form of CAD) of a multitude of alternative designs, which are needed for the assessment of the designs' behaviour.

While CAD models are difficult and expensive to edit for radical design changes (Woodbury and Burrow, 2006; Heikkinen, Johansson and Elgh, 2018), engineering design research has always presented other approaches to generate, capture and assess innovative ideas and stimulate the creativity of product developers in the problem solving process (Pahl *et al.*, 2013). One way to capture such ideas are function models (FM), which provide a flexible way of correlating different functions, solutions, and systemic product properties (Gero, 1990). While function modelling does not provide rich geometric information (compared to CAD models), FM can provide information about the product structure and be an intermediate step between the ideation and realisation process. While the use of FM for design space representation and analysis is not novel as such, most approaches only perform modelling and analysis in the function modelling domain and do not include analyses requiring geometric representation. Hence, the concepts represented in the respective function models can be analysed for systemic properties, but not other critical product properties such as structural integrity, thermal deformation or aerodynamic performance which all require geometry model-based simulation and analysis.

Based on these challenges, this paper aims to answer the following research question:

How can the effort to evaluate novel product concepts in the conceptual phases be reduced to allow for the analysis of a wider range of product concepts?

This paper reports from an industry-academy collaborative design study of a jet engine sub-system with the aim to explore alternative and novel solutions using novel technologies. A combined function and geometry model approach is used for the exploration and evaluation of different novel designs.

Following the presentation of the method applied in the study in section 2, the applied functional modelling approach is introduced and alternative ways to generate geometric concepts are briefly reviewed (section 3).

In section 4 the case example and findings of the study are presented, and section 5 discusses the implications and generalisations from the findings, as well as their relation to similar approaches and feedback from practitioners. Lastly, section 6 provides concluding remarks and an outlook for future work.

2 METHOD

This study is a result of research activities conducted in cooperation with an aerospace manufacturer, two universities and a national research institute. The 18-month research study focused on how novel technologies can be integrated into conceptual designs of aerospace components. In the first phase of the project, development requirements and project objectives were clarified. In this initial design space exploration, different design solutions had been captured through five collaborative workshops between the company's engineers and the researchers from institutes and universities. The output from the workshops were twofold. First, they represented joint activities that drove the actual development project forward, and secondly it provided occasions for participatory observations (Gero and Kan, 2016) in an action research mode (Avison *et al.*, 1999).

This paper reports on how the conceptual ideas were captured and then represented in an Enhanced Functions-Means (EF-M) model, and how this model was used to narrow down the feasible design space. Based on the EF-M model the generation of alternative CAD models was initiated. In addition to the workshop findings, eight one-hour interviews were held with the objective to learn about both the current practice of exploring alternative concepts, and in what way they saw benefits and constraints with the current work practice. The interviewees were product developers, method developers, discipline specialists and managers from both the research and development (R&D) as well as operations department of said company. The interviews were held in a semi-structured fashion, being guided by a set of lead questions but providing room for the interviewees to go in-depth on specific points that seemed of interest for the interviewers or important to the interviewee (Williamson and Bow, 2002). The interviews were recorded and transcribed. They are used in the form of representative quotes, selected along the guidelines for qualitative data analysis as prescribed by Miles and Huberman (2014), to support the discussion section of this publication.

This is a study in the context of a larger project with the goal to improve design space exploration for complex engineering products. The overarching project is organised based on Design Research Methodology (DRM) as proposed by Blessing and Chakrabarti (2002). This specific publication is a contribution to the descriptive study 1, describing the as-is status of industrial practice and analysing current challenges and trends, as well as providing an initial contribution to the prescriptive study, proposing the introduction of FM for generation and evaluation of design alternatives.

3 LITERATURE REVIEW

While most product development processes are iterative and evolutionary and build on a single legacy design (Wyatt, Eckert and Clarkson, 2009), Sobek *et al* (1999) demonstrated the benefit of developing a feasible set of candidate designs, and eliminating un-feasible ones as more information is gained. This principle, so called set-based concurrent engineering (SBCE) aims for a faster and more robust product development process by considering multiple design solutions in parallel, increasing the availability of alternative designs (Al-Ashaab *et al.*, 2013). While the application of SBCE aims for a robust product development process, design space exploration (DSE) starts from the premise of infinite possible designs which need to be explored and evaluated (Woodbury and Burrow, 2006), even increasing the number of alternative designs to be generated and analysed.

While SBCE and DSE both illustrate the use and usefulness of multiple alternative designs, the challenge to create models for such a host of designs composed of fundamentally different solutions remains.

The common way to capture novel product ideas is in the form of sketches (Boujut and Léon, 2005), where concepts and ideas are denoted and developed in a “dialogue” between sketch and engineer to the point of sprouting further, novel ideas (Brun, Masson and Weil, 2018). However, this approach to representing design concepts is not sufficient for an evaluation of the behaviour and performance of the concept (Pahl *et al.*, 2013).

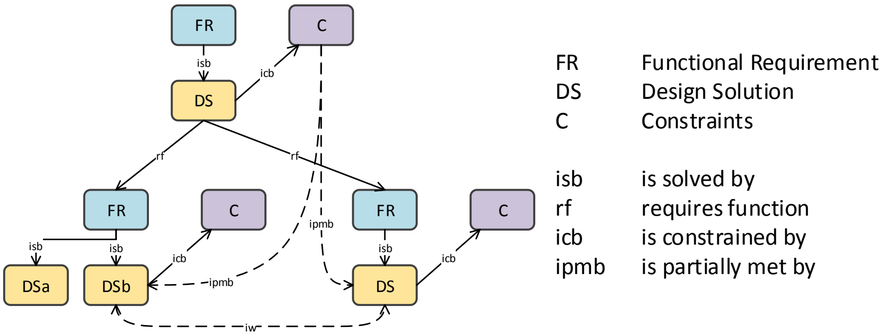


Figure 1. EF-M modelling elements, redrawn after Schachinger and Johannesson (2000).

Function based approaches start by representing the product through its function, and explore the search space on a function- and solution level (Gero and Kannengiesser, 2004). Enhanced-Function Means (EF-M) modelling is a function modelling method which is capable to represent a product’s design rationale based on function-solution relationships (Schachinger and Johannesson, 2000). While following the one-to-one matching of solutions to functions as prescribed by the axiom of independence by Suh (1990), the method is capable to represent multiple alternative solutions for a single function, therefore representing a bandwidth of product concepts on different levels of detail (Levandowski, Raudberget and Johannesson, 2014). The modelling elements of EF-M are illustrated in Figure 1, including an example of modelling the alternative solutions DSa and DSb in the bottom left corner.

While other FM approaches, such as by Jin and Li (2007), Helms and Shea (2012) or Eisenbart *et al.* (2017), do manage to cover a large bandwidth of alternative solutions and already provide first-order analysis based on the product information and systemic properties captured in the models, they do not enable the simulation and therefore assessment of critical aspects of product behaviour which requires geometric modelling. Examples for this are thermal, aerodynamic or structural behaviour which are of utmost importance to the assessment of especially aerospace products (Isaksson *et al.*, 2016). Furthermore, while some approaches iterate the design process towards the component level (Helms and Shea, 2012), the actual embodiment, which is needed for product behaviour analysis, is rarely mentioned or performed. CAD models, on the other are in their structure too rigid to account for multiple alternatives, "made for drawing, not design" (Woodbury and Burrow, 2006). Woodbury and Burrow (2006) further describe the challenges of altering CAD models, which are the most common models in engineering design, to include a variety of designs. This is further supported by e.g. Heikkinen, Johansson and Elgh (2018), which state the difficulty of integrating novel solutions into an existing CAD model as a challenge to multidisciplinary exploration of design alternatives.

Using design automation (DA) and knowledge-based design (KBE), the rigidity of CAD models can be circumvented by applying programming routines and parameterisation (Verhagen *et al.*, 2012), which enable the creation of a set of variants based on a so-called master model. Sandberg *et al.* (2011) present a framework for the generation of dimensionally different variants of a turbine rear structure, while Shea, Aish and Gourtovaia (2005) present an approach to generate different architectural support structures. Both approaches build on a master-model which is a highly complex CAD models containing all possible variants and variations, which thereby defines the search space of the exploration process. Furthermore, multi-disciplinary analysis (MDA) systems are employed to generate knowledge about the variants behaviour, and supporting engineers' decisions about the design. However, while many of these approaches are showing promising results, few of them have been realised in industrial application (Rigger and Vosgien, 2018).

4 RESULTS

First, a selection of findings from the initial design study is presented together with the details of the case study, where after the combined function and geometric modelling approach and its results are explained.

4.1 Case study and generation of novel concept alternatives

The product used in the case study is a turbine rear assembly (TRA) of a commercial aircraft engine. This type of product is developed and produced at the case company since many decades. As a result, there is an extensive body of experience in the respective design teams. The TRA is composed of the turbine rear structure (TRS), the cone, the low-pressure turbine (LPT) fairing and the aft-fairing, as illustrated in Figure 2.

LPT fairing, aft-fairing and cone primarily serve an aerodynamic function. The TRS, while also having the aerodynamic function of reducing swirl in the airstream, is a structural, load bearing component, positioned after the last turbine stage in the jet engine.

In two initial workshops, concepts and ideas were generated with the aim to introduce novel technologies into the TRA thereby developing a more valuable product. Main drivers for this introduction of novel technologies were expected increased thermal loads for future engines, as well as goal to introduce new material technologies. Ideas were collected in classic workshop mechanisms such as group-based brain-storming and collected on post-its and on posters.

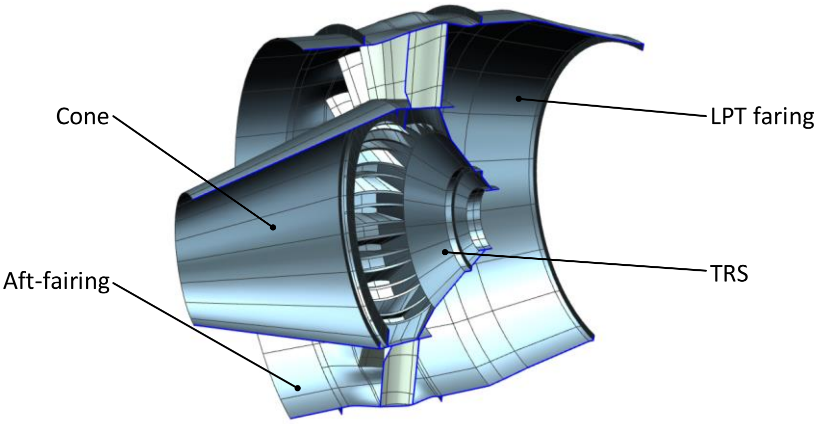


Figure 2. TRA in original design as rendered CAD shell model, section through the XZ plane. The aircraft's flight direction is from left to right.

As a sample for such a new concept, Figure 3 shows four different solutions for the connection of the cone to the TRS when using materials with thermally different behaviour. In the workshops, the concepts were captured in the form of sketches, as an example of how engineers already in the conceptual design phase tend to work with geometrical representations. The sub-system design concepts shown for the interface are the result of a design choice on a higher level, where the material of the cone is substituted with a ceramic-composite material which shows different thermal behaviour than the Inconel alloy used for the TRS. The example shows that while the sketches in themselves provide valuable technical solutions, these are only valid in the context of this specific challenge.

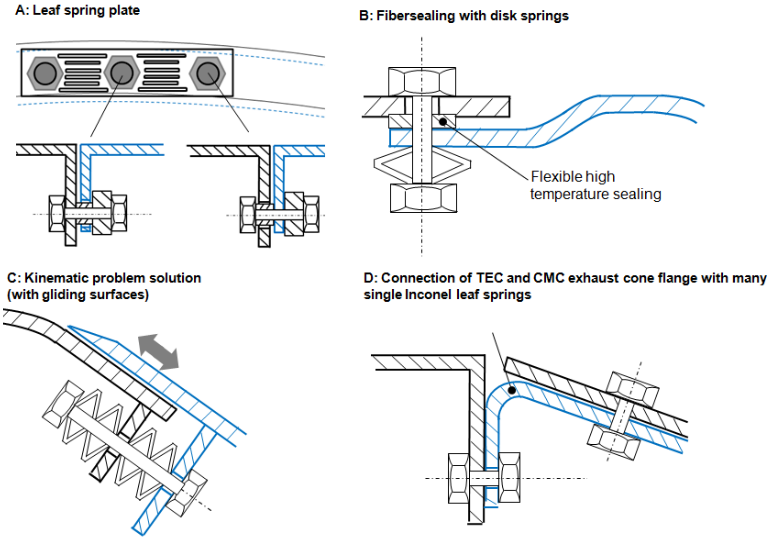


Figure 3. Sub-system solutions A through D for the connection between two materials with different thermal expansion coefficients, collected from the initial ideation process. Final drawings are courtesy of RISE IVF.

4.2 Representing novel concepts simultaneously: a function modelling approach

To enable the implementation of novel concepts into an existing product architecture, the product needs to be represented first in a way such that the model can easily be manipulated, and new functions and solutions can be inserted, on both different levels of maturity as well as on different levels of product hierarchy. Furthermore, the product representation needs to be able to represent both the legacy design as well as the novel introduced solutions, to be able to compare them against each other.

Although the legacy design is available in a CAD model, this model would be too rigid to capture all the novel design solutions in it. The time and effort needed to implement all of them into CAD is exactly the limitation for design space exploration mentioned in the problem statement above. Making use of the flexibility and easy editability of function modelling methods, an EF-M model is created instead. This allows to illustrate the complex product structure and also for the introduction of novel solutions on different levels of the product detail levels. At first, the legacy TRA structure was captured in an EF-M model. Based on the workshop results such as illustrated in the example in Figure 3, new branches were added to the EF-M model shown in Figure 4. This extension of the existing product models with novel solutions is performed by adding a new DS onto the respective FR. This novel solution substitutes the existing one, and the overall design can be instantiated using either of the solutions, as long as they conform the constraints also captured in the EF-M model. This is illustrated on the example of the additional material options for the cone in Figure 4.

Depending on the level of novelty of the ideas, new functions or solutions were added. While most new ideas only substituted or improved existing solutions while keeping the original functionality of the product, other solutions added entirely new functions which had not been covered by the TRA but by other sub-systems of the jet-engine. An example for this is the introduction of a generator into the TRS hub geometry to generate electric energy, a function which was previously fulfilled by another engine component. The following section describes two main benefits of using such functional modelling approach: the possibility to link existing product information and the possibility to generate information from function modelling,

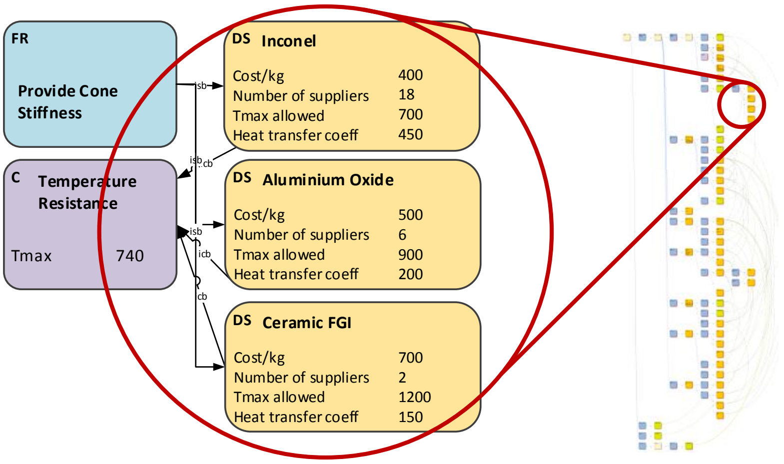


Figure 4. EF-M model including all existent and novel ideas together with their interaction. FR are blue, DS yellow and C purple. Enlarged on the left different material solutions for the FR "provide cone stiffness", including solution specific data. Illustration captured from CCM modeller. Enlarged elements redrawn for readability.

4.3 Assessment of design alternatives in the function modelling domain

Together with the structuring and relations of the novel and legacy functions, already available product information about these solutions was captured in the model. This knowledge was gathered from previous studies with the legacy design, data sheets and engineering experience from the experts participating in the workshops. An example of this is shown on the left in Figure 4, where three different material options for the cone in the EF-M model are detailed with the available information for the FR "provide cone stiffness".

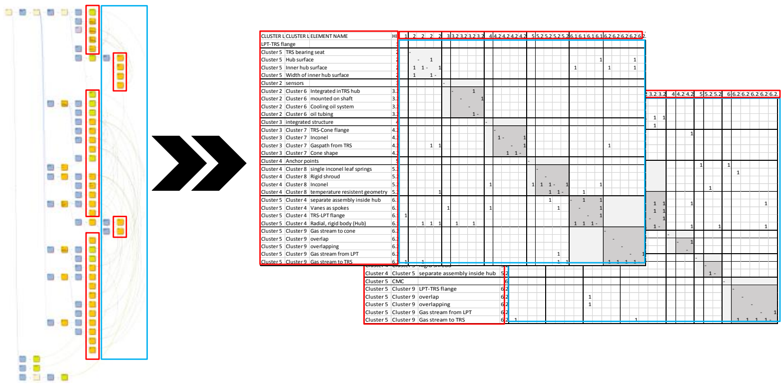


Figure 5. Clustered DSM to compare different modularisation of two variants created from information stored in the EF-M model. Blue boxes highlight the connections between different elements in both EF-M and DSM, while red boxes show the elements themselves.

The capturing of available product knowledge together with the systemic information stored in the EF-M model in the form of interactions and hierarchy allowed for an initial screen of the alternative concepts. As an example for the available systemic information, Figure 5 presents the clustered design-structure matrix (DSM) of two alternative concepts, showing the different modularisation possibilities of two concepts and how the DSM are derived from the EF-M model.

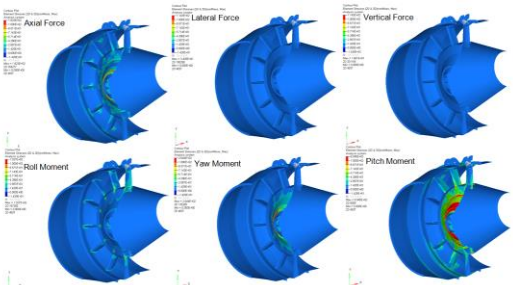
The modelling of constraints derived from product requirements and through the legacy product's decomposition enables an initial filtering of the available concepts. Constraint values are parameterised and can be adapted to respective use cases or changes of requirements throughout the design process, which are to occur commonly. Shown Figure 4 is a constraint with parametric values, which enables the filtering of solutions depending on use case. If the requirements, as is shown in the figure, prescribe an environment temperature of 740°C, all concepts using the Inconel DS turn invalid, since the parameter "Tmax allowed" is set to 700°C. This mechanism allows already for an initial screen of the large number of available concepts via constraints and requirements.

The application of constraints and initial filters reduced the number of relevant designs from 1080, as would be in a full factorial combination, to 102 concepts.

4.4 Subsequent creation of geometry models for further analysis

The combination of design solutions in the EF-M models generated 102 initially feasible concepts, which needed to be evaluated according to different multidisciplinary objectives such as weight and low-cycle fatigue. These types of design evaluation require the simulation of geometry models.

To enable such design evaluations, three concepts were selected for further development and assessment. These concepts were selected due to their outstanding performance based on the function model analysis.



	x[kN/mm]	y[kN/mm]	z[kN/mm]	Mx[kNm/rad]	My[kNm/rad]
Bearing-Flange	31.77	38.31	36.56	2010.03	1091.58
Engine-Lugg-Right	1.30	21.72	33.63	106.01	30.78
Engine-Lugg-Middle	1.30	20.58	41.53	106.58	39.20
Engine-Lugg-Left	1.27	21.24	34.88	105.85	25.88
Outer-TFlange	81.00	60.73	59.31	82971.03	10898.46
Inner-TFlange	35.50	35.88	35.48	2149.26	3666.81
P-Flange	129.71	103.42	103.42	111584.45	19192.21

Figure 6. Stress analysis illustration and numeric results for loading of bearing flange of exhaust cone in a TRA design with 14 vanes. Simulations were performed by RISE IVF.

The three concepts selected for simulation and analysis were based on the three material variants for the cone sub-assembly: Inconel, Aluminium Oxide and Ceramic FGI (compare Figure 4). Beyond that, each of the three material alternatives was varied in selected geometric parameters such as number of vanes. These variations were created automatically via the parameterised master model mentioned above. Using the CAD models, analyses were performed for thermal expansion, modal analysis of the assembly, ultimate load capability, thermal shock and steady state dynamics. As an example, Figure 6 shows the results of simulation of loading the bearing flange of a concept with an Inconel cone and 14 integrated vanes.

All geometry related parameters captured in each EF-M model were extracted into a spreadsheet which served as the basis for the generation of parameterised CAD models for further simulation.

Eventually, three different material solutions in each three parametric variations were analysed and the data used for a value assessment of the different designs.

The results of the simulations were integrated into the function model, extending the systemic product information already available, and aggregated using a QFD-like matrix in order to provide the "design merit" of each concept (Bertoni and Bertoni, 2016).

4.5 Practitioners feedback

Right after the workshops the function model and the working approach has been discussed with different practitioners, and to a later time individual interviews with practitioners in key roles were performed. These interviews were recorded, transcribed and analysed based on the categories "state of the art", "current challenges", "CAD" and "function modelling". The following gives an overview over the different positions by use of representative quotes.

According to the majority of interviewees, the approach described above, i.e. a system to analyse the impact of design changes and alterations early on in the design process, “is what the whole industry sort of aims for”. The statement that the CAD model is too rigid was supported by all interviewees, stating that attempting a wider variation of it makes the model “very complex and […] hard to work with”. This, and the acknowledgement that for novel designs new CAD models are required, contributes to the proposed need for a new modelling method to ease the effort of representing novel designs in a more efficient way. However, the current practice of CAD as the backbone has not been questioned before, as it “is in the centre of everything”. This hints towards challenges if aiming to introduce the approach for wider validation studies, as furthermore the concept of “function” appears to be too abstract, and apparently “many engineers are not comfortable with abstraction”. However, a manager stated that such an approach “definitely has an important role to play in order for us to quickly iterate different design solutions”.

5 DISCUSSION

The case study described above illustrates an approach to assist product developers in exploring more alternative design concepts with a higher bandwidth of technical solutions. This was accomplished by introducing a function model into the process of design space exploration.

Where in product development processes in industry an existing product’s geometry is varied to fulfil a new set of requirements, which limits the amount of investigated new designs as described above. The approach presented here allows for a wider and more systematic design space exploration. Instead of building onto the legacy design’s form, the redesign builds onto its teleological structure, and uses this as the basis for the generation of new geometries. Other function modelling based approaches have been shown by Eisenbart, Blessing and Gericke (2012), Jin and Li (2007) or Helms and Shea (2012). In these approaches, however, the development of novel designs remains in the function modelling domain. The approach presented here, while also making use of the systemic information of the function model, recognises the need for simulation and analysis based on geometric models, and therefore extends the modelling approach into the geometric domain. The information captured in the function model is used to aide in generating geometric models and supports a design automation approach based on parametric CAD. While e.g. the Contact and Channel Approach (C&C²-A) as presented by Albers and Sadowski (2014) also shows a connection between geometry and function, is does not pursue an exploration of alternative designs in both domains.

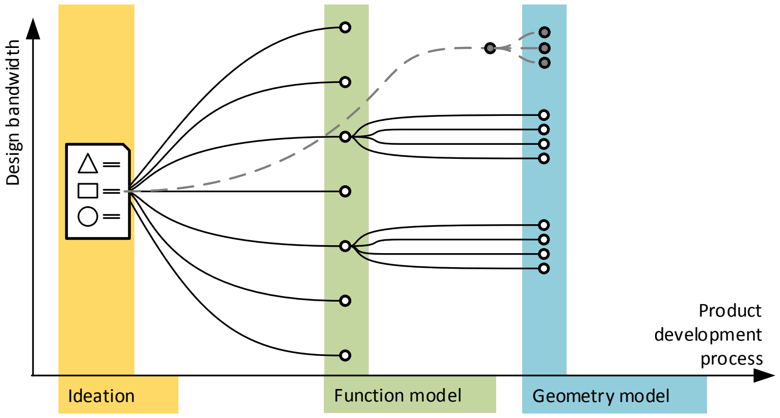


Figure 7. Illustration of suggested DSE approach using an intermediate function model.

Seen in the context of a product development process, as illustrated in Figure 7, the approach adds an additional modelling step between ideation and embodiment. The traditional approach, as observed in practice and confirmed in the interviews, illustrated in a dashed grey line in Figure 7, leaps from ideation (yellow bar) into the variation of the existing geometry (blue bar). As is illustrated in this figure, and has been shown in the presented study, the function model is capable of covering a wider range of alternative designs and supports developers in the selection of relevant concepts for further development. The approach explained in this paper, however, provides a more systematic approach by capturing both the legacy design, as well as the results of the ideation process in the same function model. The function modelling domain is illustrated in the green bar. In this stage, an initial but systematic concept filtering is performed based on the available product information.

In the described study the approach has been applied in an industrial product development environment on one product in a set of workshops. While the follow up interviews with practitioners show a tendency towards the benefit of the approach, further studies are required to validate it.

As stated about the lack of a mechanic to generate geometry models for all the concepts explored in the functional domain is a drawback, the approach is a first step away from the evolutionary product development processes which is common in industrial practice. It furthermore approaches a systematic knowledge capture, where in the current day processes not finding relevant development information is “definitely a risk”. This is done by the systematic capturing of the product’s functions of both legacy and novel design. Further development processes would not need to decompose the legacy design again, but can build onto the available function models including not used, already mapped out solutions.

6 CONCLUSIONS

This case study has demonstrated a way to systematically capture design alternatives in a function model and integrate them with a legacy model, thereby matching the approach of industry practice in product development. The function model is successfully used to evaluate the alternative concepts on a systemic level, capture available product knowledge to support the assessment of the designs and used as a basis for the generation of CAD models for the necessary simulations and analysis of concept behaviour which could not be simulated in the EF-M model.

The approach claims to be more systematic than the product development processes currently applied in practice. This is achieved by capturing both the legacy product as well as the novel concepts in one function model, which represents the product’s architecture and the systemic implications of the introduction of novel ideas. This representation already allows for a systematic initial analysis of the alternative concepts, and therefrom a screening of the available concepts, using e.g. DSM for an analysis of the modularity and complexity as well as the captured quantitative product data in the individual solutions. Furthermore, although the creation of geometric models is still subject to manual engineering work, the available parameters in the different solutions have been used for automated parametric variation of the CAD models which in turn have been used for the multi-disciplinary analyses.

While the presented set of interview results does not provide a reliable validation of the approach, it shows that it is approaching a real problem and provides solutions which are appreciated in their workings by practitioners.

It can be concluded therefrom that the presented approach allows for a systematic generation and analysis of structurally and functionally different solutions of different levels of maturity.

However, to be able to integrate it into a practicable product development process and to reduce the above-mentioned challenges of too rigid CAD models, further research towards the integration of design automation mechanisms into the approach are necessary – as has been stated in the interviews: “automation of the engineering process is key”.

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