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# Towards automated conceptual design space exploration

An investigation into the design process of aerospace components

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Cover:
Illustration of design space exploration building on legacy geometry models through the use of intermediate function models in front of a render of a Turbine Rear Structure (TRS). See page 2 and page 31 for details.

*„Allwissend bin ich nicht; doch viel ist mir bewusst.“*

*„ Omniscient I am not, but much is known to me.”*

— Mephisto in Faust, J.W. Goethe

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# Abstract

In mature and safety-concerned industries, such as the aerospace industry, product development is often incremental and design solutions are limited to improvements of an existing design. Radical changes to the known product architecture are avoided, for reasons of reliability, lack of technology or lack of design space exploration (DSE) methods. This thesis aims to investigate into the challenges for DSE, and how it can be improved to be faster, wider and more systematic.

This research has been undertaken in four different research projects, addressing the challenges of the aerospace industry.

The process of exploring the design space, the set of all possible designs, can be divided into three phases: to define the design space boundaries, to populate this design space with concepts, and lastly, to analyse the different concepts to find the one which provides the highest value. A deficiency in the description of functions and constraints which constitute the design space dimensions and boundaries, rooted in the lack of methods, has been identified to reduce the available search space already in the beginning. To populate this search space, developers need to generate representations of their new designs. These representations, commonly 3D geometries in the form of CAD models, are too rigid in the form they are used today. Therefore, it is expensive to create many variants, which differ in solutions and shape. This reduces the design space population to only a few concepts, derived from the legacy design. The analysis of alternative concepts is challenged through different maturities and variety of concepts.

The coverage of multiple hierarchical search spaces, from geometry over solutions to value, has been identified as a driver for wider DSE. Furthermore, the need for a product development approach that is capable to bridge the levels of modelling abstraction. Enhanced Function-Means (EF-M) modelling, a function model applied in all studies referenced in this thesis, bridges the abstraction from a verbal description to a teleological graph, while enabling a more systematic capture of the design space boundaries. However, a subsequent gap towards geometry models could be observed in all studies. This hindered a faster design space exploration, since extensive manual labour is required to bridge these abstraction levels.

For further work, the closing of the abstraction gap in the product modelling methods is seen as the primary goal for further work, either by extending the already applied function- and geometry modelling methods, or by including other frameworks.

**Keywords**: Aerospace, Design Automation, Design Space Exploration, Engineering Design, Function Modelling, Function-Means Modelling, Geometry Modelling, Knowledge Based Engineering, Model Abstraction, Model Based Design, Product Development, Systems Engineering

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*This could not have been achieved without the help and support of many.*

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Last but not least, thank you Elena, for going through this PhD process together with me.

# Appended Publications

**Paper A**   Isaksson, O., Bertoni, A., Levandowski, C. E., **Müller, J. R.**, Wiklund, D. and Johannesson, H. (2016). Virtual contextual validation of technologies and methods for product development, in *Proceedings of International Design Conference, DESIGN*, pp. 669–678.

**Distribution of work:**

Jakob Müller contributed with sections for the results and discussion. Ola Isaksson conceptualised the paper and coordinated the contributions from the other authors.

**Paper B**   **Müller, J. R.**, Panarotto, M., Malmqvist, J., and Isaksson, O. (2018). Lifecycle design and management of additive manufacturing technologies. Procedia Manufacturing, 19(2018), 135–142

**Distribution of work:**

Jakob Müller conceptualised the paper and coordinated the contributions of the other authors. Massimo Panarotto wrote the methods section, as well as researched and wrote the frame of reference. Johan Malmqvist and Ola Isaksson contributed with knowledge and critique to the papers concept and form.

**Paper C**   Borgue, O., **Müller, J. R.**, Panarotto, M., and Isaksson, O. (2018). Function modelling and constraints replacement for additive manufacturing in satellite component design. *Proceedings of NordDesign 2018.*

**Distribution of work:**

Jakob Müller and Olivia Borgue conceptualised and wrote the paper together. Massimo Panarotto contributed to the methodological section. Müller developed and illustrated the function modelling approach and Borgue researched and wrote the additive manufacturing background and contribution.

**Paper D** **Müller, J. R.**, Isaksson, O., Landahl, J., Raja, V., Panarotto, M., Levandowski, C. E. and Raudberget, D. (2018). Enhanced function-means modelling supporting design space exploration, *Artificial Intelligence for Engineering Design and Manufacturing,* (submitted)

**Distribution of work:**

Jakob Müller wrote the majority of the paper and illustrations, conceptualised the framework and orchestrated the contributions. Ola Isaksson contributed to the methodical approach, discussion of the results and scientific contribution. Jonas Landahl wrote the dissemination of innovative and reverse engineering, Visakha Raja contributed with the explanation of the reverse engineering of integrated systems. Panarotto, Levandowski and Raudberget contributed with knowledge, writing and critique to various sections of the paper.

# Table of contents

# List of abbreviations

| | |
|---|---|
| **2D** | Two-dimensional |
| **3D** | Three-dimensional |
| **AI** | Artificial Intelligence |
| **AM** | Additive Manufacturing |
| **CAD** | Computer Aided Design |
| **CC** | Configurable Component |
| **CCA** | Contact and Channel Approach |
| **CCM** | Configurable Components Model |
| **DA** | Design Automation |
| **DEE** | Design and Engineering Engine |
| **DoE** | Design of Experiments |
| **DR** | Design Research |
| **DRM** | Design Research Methodology |
| **DS** | Design Solution |
| **DS1** | Descriptive Study 1 |
| **DS2** | Descriptive Study 2 |
| **DSE** | Design Space Exploration |
| **EF-M** | Enhanced Function-Means |
| **EoL** | End of Life |
| **EVOKE** | Early Value Oriented design exploration with KnowledgE maturity |
| **EWB** | Engineering Workbench |
| **FBS** | Function-Behaviour Structure framework |
| **FEM** | Finite Element Modelling |
| **FM** | Function-Modelling |
| **FR** | Functional Requirement |
| **HLP** | High Level Primitives |
| **KBE** | Knowledge-Based Engineering |
| **MDA** | Multi-Disciplinary Analysis |
| **MDO** | Multi-Disciplinary Optimisation |
| **PS** | Prescriptive Study |
| **RQ** | Research Question |
| **SBCE** | Set-Based Concurrent Engineering |
| **TRS** | Turbine Rear Structure |

# 1 Introduction

*Explaining why we actually need this kind of research, and what it is about.*

"Products are artefacts [...] used by people because of their properties and the function they may perform" (Roozenburg and Eekels, 1995). Conclusively, product development is the process to conceive the idea of such an artefact, which has the desired properties and performs the expected functions, and to mature this idea to the point where it can be manufactured. The better the product's behaviour matches the desired function, the higher its value – the more benefit it brings to the involved stakeholders, such as users, manufacturers and suppliers. However, it is a challenge to define an artefact in such a way through its shape, make and material that it performs a desired function – while still conforming to the all imposed constraints. This is especially true with product development growing in complexity and expected performance, both of the product itself as well as of the development process.

In the year 1930 Sir Frank Whittle submitted the application for the first turbojet engine. A novel way to propel airplanes, developed and realised by a single inventor (The Sir Frank Whittle Commemorative Trust, 1999). Almost a century later, aircraft are propelled by the same principle – air is compressed, fuel injected, and the expansion of the ignition rotates a turbine, which in turn propels the initial compressor as well as the aircraft. The process is illustrated in Figure 1.1.
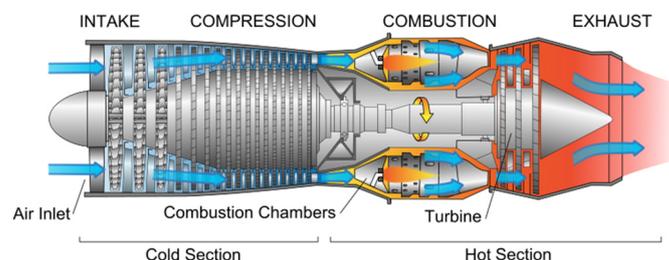


Figure 1.1 Diagram of a gas turbine jet engine. Air is compressed by the fan blades as it enters the engine, and it is mixed and burned with fuel in the combustion section. The hot exhaust gases provide forward thrust and turn the turbines which drive the compressor fan blades.[1]

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[1] Image and description from Wikimedia Commons, author: Jeff Dahl

To fulfil these changing functional requirements and constraints, developers need to generate new solutions and concepts. Therefore, they need to first define what these required functions and constraints are, which is according to Suh (1990) the most difficult and important step of product development. Through this, they define their so called design space, which contains all potential solutions (Saxena and Karsai, 2010). Now the developers need to find solutions which are both inside this design space, and then test these solutions whether they comply with the requirements and constraints, and also provide a higher value then the last product. However, this design space is "hyperastronomically vast" (Woodbury and Burrow, 2006),  and for novel and radical concepts, which might be very promising in terms of performance and value (Lawson and Samson, 2001), little is known about their behaviour and the implied risks and chances. Therefore, product developers often remain close to the original product design and follow the system administrator wisdom "never change a running system". This leads to an evolutionary development which does resolve in incrementally better products, but also reduces the margins for optimisation with every product generation.
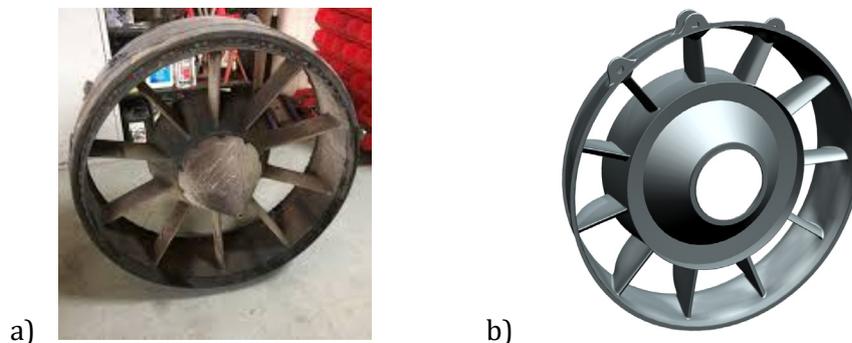


a)          b)

Figure 1.2 Turbine Rear Structure, a) from a Rolls Royce Conway jet engine from 1959 [2], b) rendering of a TRS as it is produced today.

 As an example, a turbine rear structure (TRS) is a structural component in the aft section of a civil aircraft engine. It provides the functionality to reduce swirl in the gas stream before release and serves as a connector of the turbine to the aircraft nacelle. The form of it is a spoked wheel with aerodynamically shaped struts, which has not changed in the last 60 years – as is illustrated in **Error! Reference source not found.**, where a design from a Rolls Royce Conway jet engine from 1959 is compared to a design from today's development process. The main changes in the product over time has been in terms of material use and manufacturing (Madrid *et al.*, 2016). However, this is not due to designers' lack of imagination, as workshops have shown – Figure 1.3 shows some of the novel ideas that have been brought up in a workshop for the VITUM project, which is explained in Chapter 3.2. The challenge lies rather in the modelling and analysing of these concepts, which is necessary to gain an understanding of their behaviour. This leads to many novel ideas not being considered for development due to perceived challenges of cost and/or risk.

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[2] Retrieved from: https://www.ebay.co.uk/itm/rolls-royce-conway-jet-engine-exhaust-/112797760036
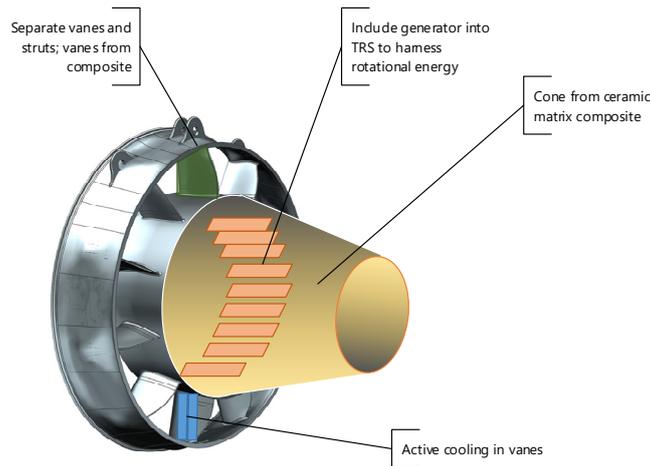
Figure 1.3 Ideas for innovations to increase value of TRS. Simplified based on results from the VITUM project

The central problem in design space exploration is that developers only explore a subset of the available design space, which is close to the legacy design. Hence, conservative designs dominate over radical designs, although these radical designs might bring a higher value. It is therefore the aim of this research to improve design space exploration (DSE) in the concept development phase of product development. The main focus is put on the use and connection of different modelling methods and different modelling domains.

## 1.1 Background

The *design space* is a metaphor that describes the set of all possible designs (Saxena and Karsai, 2010). It can be imagined as a multi-dimensional space, where each dimension describes a design parameter, and each design is a point in this space, defined through its design parameters as coordinates. While space is theoretically infinite, the design space commonly is not - it is limited by different factors, so called constraints, which act on the range of specific design parameters. It contains, however, nearly infinite design concepts (Woodbury and Burrow, 2006). Examples for constraints can be a maximum or minimum weight, which would act on the design parameter "mass". Figure 1.4 illustrates the concept of the design space on a design with 2 parameters DP1 and DP2, and 4 constraints – C1, C21, C22 and C3. The orange area illustrates the design space containing feasible solutions (A, B, C). Concept *D* is unfeasible since it violates constraint C3.



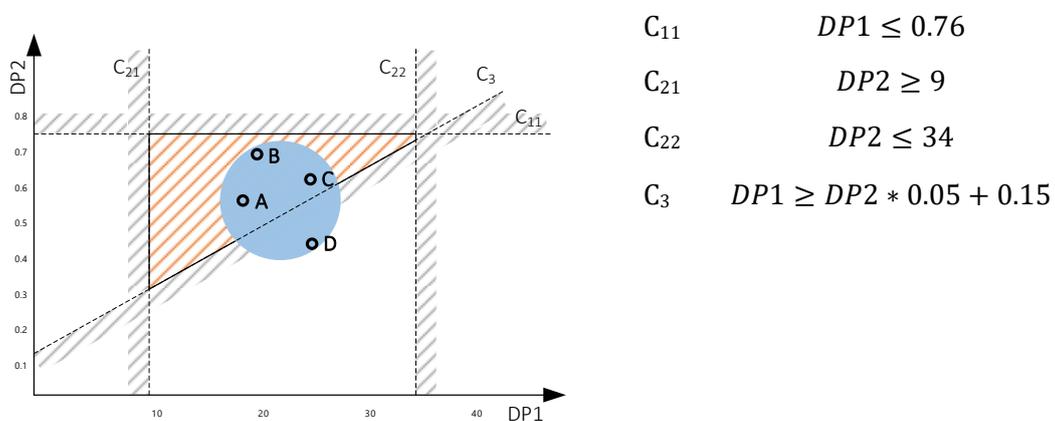| | |
|---|---|
| $C_{11}$ | $DP1 \leq 0.76$ |
| $C_{21}$ | $DP2 \geq 9$ |
| $C_{22}$ | $DP2 \leq 34$ |
| $C_3$ | $DP1 \geq DP2 * 0.05 + 0.15$ |

Figure 1.4 Design space illustration for two parameters with constraints. The orange area illustrates the feasible design space, the blue area the search space.

While the design space contains all possible solutions, the *search space,* which resides in the same domain, describes the solutions which are actually considered in the product development process – the blue area in Figure 1.4. The search space does not necessarily have to be a sub-set of the design space, since during the product development process solutions are evaluated which eventually turn out to be infeasible, such as concept D in Figure 1.4. However, the search space is almost always smaller than the design space (Woodbury and Burrow, 2006).



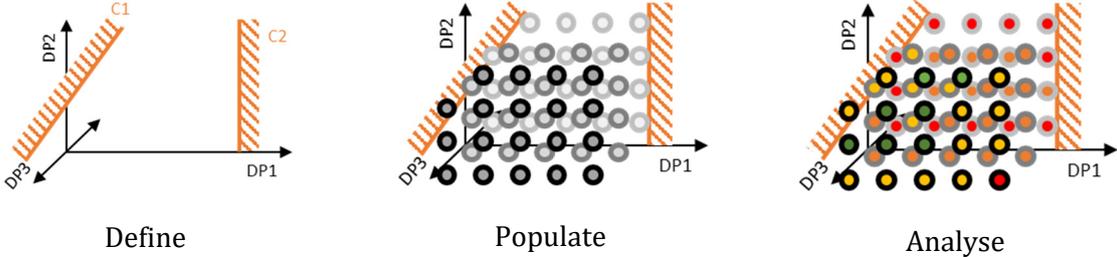| Define | Populate | Analyse |

Figure 1.5 Design space exploration phases and description

Different strategies can be applied to explore the design space. Their respective approaches can however be summarized into three steps: to define the design space, populate it with concepts and lastly analyse them for constraint compliance as well as to assess their performance to decide on which designs to pursue further. These three steps, illustrated in Figure 1.5, are similarly described by (Kang, Jackson and Schulte, 2011) for design space exploration, but are also in accordance with the general product development guidelines as found with Pahl et al (2013):

- "Define the goals" and "Clarify the boundary conditions"
- "Search for variants"
- "Evaluate based on the goals and the requirements"

While these steps are sequential, there may be several iterations of them, each refining the results of the previous. Based on this, Figure 1.5 shows an idealised illustration of design space exploration. The design space is defined through three different design parameters and two constraints, and the entire area is evenly populated with designs in different configurations. The different colours of the points in the Analyse section illustrate the results of the analysis process, where green concepts are better than red ones.
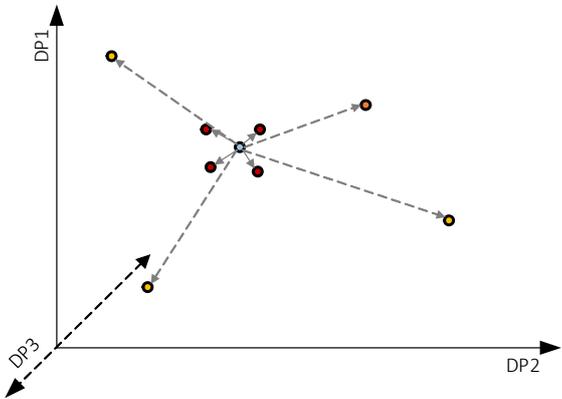


Figure 1.6 Design space exploration as observed. Points represent design.

4

**Error! Reference source not found.** on the other hand aims to illustrate how product development can be observed in practice. Starting from a legacy design, the blue dot, variations of this design are developed in the closest proximity. Potential new dimensions of the design space, such as DP3, may be ignored, as well as designs laying further away from the legacy design, in yellow.

## 1.2 Research questions

The work presented in this thesis aims to enable product developers to generate and evaluate more and especially more radical product concepts and solution alternatives in the conceptual product development phase. Based on this premise, the following research questions (RQ) are posed for this thesis:

*RQ1: What are factors limiting product developers in exploring the design space in the concept development phase?*

The first questions aims to investigate the challenges and resulting needs for product developers. A second question is posed to find solutions to the identified challenges and pave the way to the development of a method that can lead to improved design space exploration:

*RQ2: How can design space exploration be improved to be faster, more systematic, and cover a wider area of the design space?*

## 1.3 Research scope and delimitations

The research presented in this thesis is concerned with the development of complex products, such as aircraft engines or aerospace components. The focus lies on the conceptual product development phases, where developers decide on which concepts are pursued into the detailed design phase. The main focus lies on the use of different product models in this phase to illustrate alternative concepts and compare them.

The descriptive part of the thesis aims to explain challenges and needs as observed in literature and through collaboration and interviews with industrial partners. These partners all reside in the Swedish aerospace industry, hence the viewpoint of this research is focused on this specific sector.

## 1.4 Thesis structure

In the following chapters, this thesis aims to generate an understanding for the topic of design space exploration as well as present the results of the appended research papers.

**Chapter 2** illustrates the state of the art in academic research, by explaining several modelling methods in different domains and abstraction levels as well as their use in multi-disciplinary analysis and optimisation. Furthermore the topic of design space exploration is elaborated.

**Chapter 3** presents the research approach this work follows. First the Design Research Methodology framework and this works positioning relative to it is explained. Secondly, the

different methods which have been applied to gather and analyse data, and lastly the validation of the results.

**Chapter 4** is composed of the summaries of the four appended papers and the key results and findings that can be extracted from them.

**Chapter 5** discusses the above mentioned findings in the context of current academic research and how the identified needs can be connected to the proposed solutions.

Lastly, **Chapter 6** concludes the thesis and proposes directions for further work, i.e. how the results of this research can be utilised towards the development of a design space exploration method.

# 2 Frame of reference

*The work of others, laying the foundation and giving inspiration to this research.*

Product development is a process of making decisions about a product while at the same time accumulating knowledge about it. Since the decisions need to be founded on said knowledge, the decisions in the early phases of the product development process have to be made based on very little knowledge. Ironically, these decisions are the ones with the largest impact on the design process. This is called the Design Paradox, illustrated in Figure 2.1: the knowledge about the design grows in the same pace as the freedom of design shrinks (Ullman, 2003). The aim of design engineering methods is to improve upon this situation: either provide more knowledge in the earlier product development phases, or enable more design freedom later in the design process.
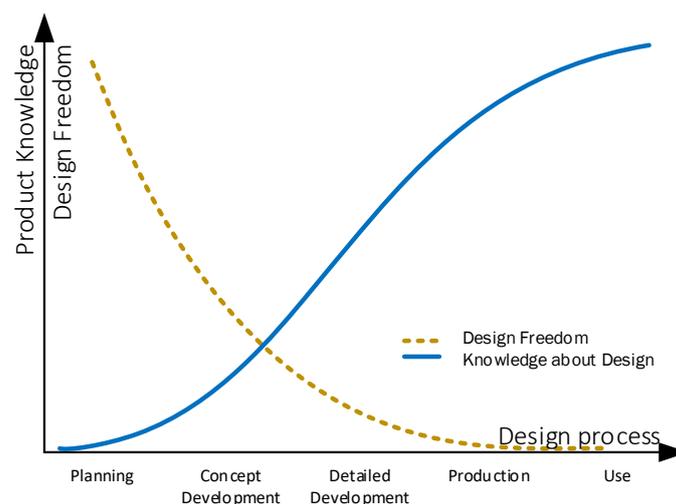


Figure 2.1 Design Paradox, redrawn after (Mavris *et al.*, 1998)

## 2.1 Product development

This thesis is mainly concerned with the activities in the concept development phase of the product development process, where concepts are generated, selected and tested (Ulrich and Eppinger, 2012). In this process, the product's requirements are established, and the functions of the product are determined. Developers then find concepts which fulfil these functions in a satisfying manner, and test them whether they fulfil the requirements. These are the main activities in the concept development phase, which is highlighted in the product development process in Figure 2.2
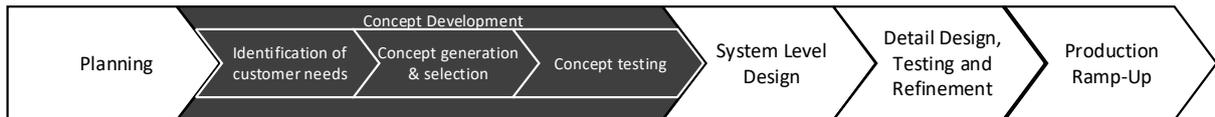


Figure 2.2 Product Development Process according to (Ulrich and Eppinger, 2012) with the concept development phases highlighted in dark grey.

While a product matures over the product development process until it is ready to be released on the market, for complex products Mankins (1995) defined a scale of Technology Readiness Levels (TRL). TRL provides a consistent comparison of the maturity of a product. Since it has its origins in aerospace product development, the terminology is respectively flight related. While it is also mainly used in aerospace companies today, terms such as "flight qualified" in TRL 8, compare Table 1, need to be adapted to the respective product environment.

Table 1 Technology Readiness Levels (TRL) after (Mankins, 1995)

| TRL 1 | Basic principles observed and reported |
|---|---|
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of concept |
| TRL 4 | Component and/or breadboard validation in laboratory environment |
| TRL 5 | Component and/or breadboard validation in relevant environment |
| TRL 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space) |
| TRL 7 | System prototype demonstration in a space environment |
| TRL 8 | Actual system completed and "flight qualified" through test and demonstration (ground or space) |
| TRL 9 | Actual system "flight proven" through successful mission operations |

### Set Based Concurrent Engineering

The notion that all elements of the product life cycle, from requirements over design and production up to use and end of life (EoL) are connected and need to be considered when developing a product is the foundation of concurrent engineering (CE) (Prasad, 1997). Combining observing the functions of a product relevant to all life cycle stages with extensive forward planning and a parallelisation of development tasks allows engineers to discover errors and potential redesigns early on in the design process (Tayal, 2012).

The combination of this holistic approach to product development with not only pursuing the development of a single concept but a set of alternative has been coined as Set-Based Concurrent

Engineering (SBCE) (Sobek Ii, Ward and Liker, 1999). SBCE is a product development approach that encourages design space exploration – by keeping alternative concepts in mind as long as they can fulfil all requirements. Figure 2.3 illustrates the SBCE approach of design space exploration – where an entire set of concepts is pursued all but one concepts have been eliminated over the design process.
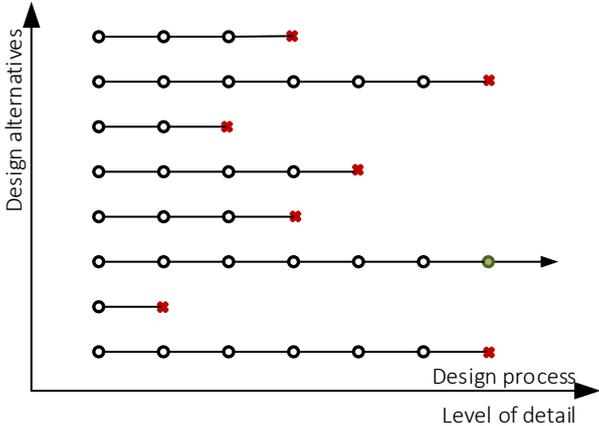


Figure 2.3 SBCE design space exploration. Each circle represents a design iteration, with increasing level of detail from left to right. Each red X illustrates the elimination of a concept. The concept with the green circle and arrow is chosen as final concept and developed further.

A "*concept*" in this context is the idea for a product, throughout the entire product development process. It includes a specified set of solutions for all functions, which makes it unique among the set of other concepts that are pursued. Different concepts may fulfil different functions and requirements. Among the concepts that are developed for the same set of requirements, *variants* are topologically different among each other, or even use different solution principles for the same set of functions and requirements. *Variations* use the same approach of solutions, but the concepts differ in dimensions and non-topological choices – such as after-treatments or material parameters.

**Value Driven Development**

A major challenge in product development is to define "what is a good design?" or "which design is better?". These questions are challenging due to the fact that a product's success is of interest and is defined by multiple stakeholders, who have different and at times opposing interests. Hence the challenge is to balance these multiple views into one function that can evaluate the value of a product concept. Value is traditionally defined as function over cost (Miles, 1972). However, function and cost need to be defined and evaluated, and can be different for each involved stakeholder.

The Value Driven Design (VDD) methodology proposes a method on how trade-offs between different stakeholder interests already in the early stages of the product development process (Isaksson *et al.*, 2013). The value of a product or technology is defined at a very high level, and needs to be iterated through the different product models to be connected to the artefact level (Panarotto, Isaksson and Asp, 2018). One method to do this is Early Value Oriented design

exploration with KnowledgE maturity (EVOKE). High level stakeholder needs are captured as well as *value drivers* and categorized in *value dimensions*, and mapped towards *engineering characteristics* which describe the product's properties, as derived from its behaviour (Bertoni, Bertoni and Isaksson, 2016). The mapping approach involves a weighing matrix each between stakeholder needs and value drivers as well as between value drivers and engineering characteristics, respecting the different levels of contribution of different product aspects towards different stakeholder needs.

## 2.2 Models in product development

Product development relies heavily on product representations: "it is now established wisdom in the engineering design community that models are useful means of understanding and interacting with both products and processes" (Eckert and Stacey, 2010). Models are "A target oriented, simplified formation analogous to the original, which allows drawing conclusions based on the original" (Lindemann, 2007). Throughout the product development process, a multitude of product models are used. They represent the product in different stages of the product development process, different levels of abstraction or different aspects of the product (Kusiak and Huang, 1996). The product development process is a process of information generation (Ullman, 2003), where the models of different product development stages gain in information-richness and reduce their level of abstraction. Commonly, models of higher level of abstraction are used earlier in the product development process, and more information rich models towards the end. This correlates with the increase of product knowledge illustrated in Figure 2.1.

The information, which reduces the level of abstraction, needs to be generated at some point. This process we call *design*. The product models gain information through the product development process, as is illustrated in Figure 2.4. Different models, which build onto each other, are presented from a research project, which is published in paper B. Their model types are used to illustrate a scale of model abstraction. A similar scale for product representation can be found with Lyu et al (2017). A physical prototype has a very low level of abstraction, it can even be experienced physically. However, it might still not contain the full information set as the entire product, hence it is still a model. The most abstract model in Figure 2.4 is a verbal description, i.e. "a bracket to lift the engine with, which can also hold a cooling tube and some wires". It is abstract, since it is not linked to a concreted product concept.
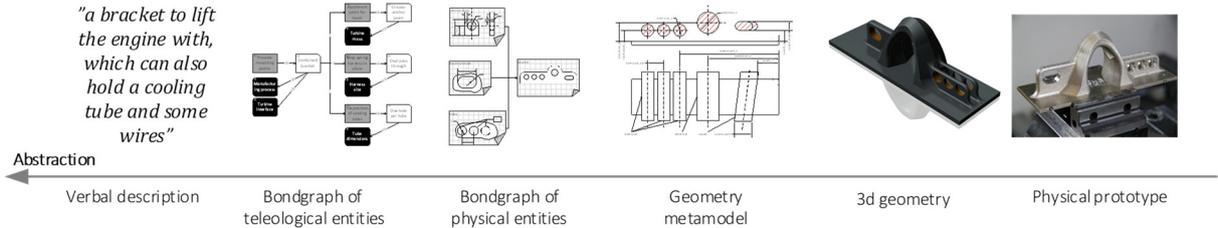


Figure 2.4 Abstraction levels of the same product "engine bracket" from paper B

## Physics models

Beyond product models, which represent the different properties of the product, physics models are used in product development as well. They describe mathematical representations of different physical phenomena, such as heat transfers, aerodynamics or structural loads. These models are applied to analyse the product's behaviour in combination with a geometry model of the product. For this purpose of analysis, the geometry models are usually converted from CAD to "mesh" models, a mathematically different representation of the geometry. An example of such a physics model is the deflection of a beam under load as illustrated in Figure 2.5.
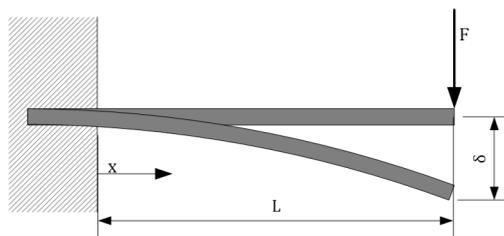
$$\delta = -\frac{Fx^2}{6EI}(3L - x)$$

With **I** the moment of inertia and **E** the Young's modulus of the material

Figure 2.5 Physics model of the deflection of a beam

## Geometry Models

Geometry models represent the shape of a product. This can be either in two or three dimensions, while these days 3D representations are the norm. 2D projections of the 3D models are often used for production documents. The most common geometry models are made via Computer Aided Design (CAD), and are therefore also referred to as CAD-models. The terms are used synonymously in this thesis. Some CAD models can be enhanced with metadata such as what material of machining process is used to generate the shape. The main use of geometry models is visualisation of the shape and being the base for further simulations that require a product shape. Depending on the modelling standard, some CAD models can represent not only one concept but bandwidth of different dimensions through parameterization.

Through the use of a software package, the designers can create, share and edit such models. The product's geometry is represented through mathematical functions, in most CAD models those are splines (Breps) and binary operations of solid bodies (Hoffmann, 2005). These form a standard set of geometric primitives which are adjusted and combined by the designer to form the desired geometry (La Rocca and van Tooren, 2007).

**Parametric CAD models** are CAD models with an additional degree of freedom in editing the represented geometry**.** That is, a model's dimensions are not fixed to the value given to them during the design process, but specific key dimensions can be edited through a specific interface. Figure 2.6 illustrates such an interface of a 2D sketch which is parameterised through the parameters *length* and *width*, which both depend on the third parameter *height*. This allows for a fast and efficient creation of dimensional variations of the so called master model. Parametric CAD is an enabler for multiple design automation approaches such as (Fischer, Kipouros and Savill, 2014) and applied in industrial application (Isaksson, 2003). Parametric CAD models allow for the fast and automated exploration of a dimensional, geometric search space.
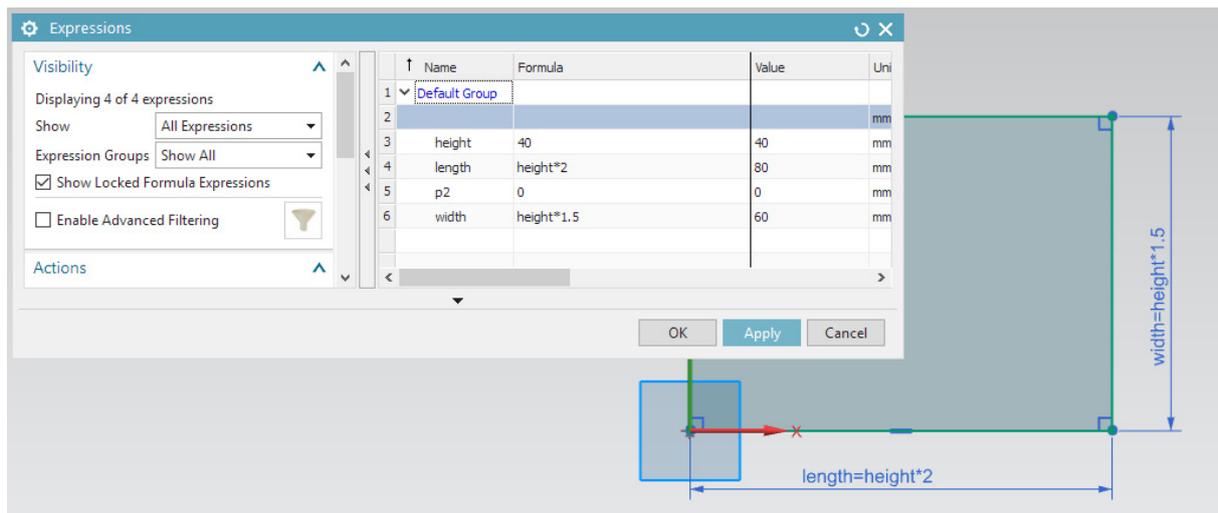
Figure 2.6 Screenshot from the CAD programme Siemens NX showing a parameterised sketch with relations between the dimensions length, height and width

**Function models**

Function models represent the teleological composition, i.e. in the intended behaviour, of the product (Gero and Kannengiesser, 2004). Although the definition of the term *function* is not agreed upon in the design research community (Summers, Eckert and Goel, 2013), in this work it is defined as "The intended behaviour of the product", analogous to (Stone and Wood, 2000) and (Gero, 1990). These models are often capable to illustrate a basic product architecture (Richter, Inkermann and Vietor, 2016), certain aspects of a design rationale and/or requirements-solution relationships (Müller, Isaksson, *et al.*, 2018). Depending on literature, function models are sometimes referred to as "functional models" (Summers, Eckert and Goel, 2013).

There is no function modelling standard in neither industrial application nor academic research (Summers, Eckert and Goel, 2013). Therefore, three function modelling frameworks are illustrated here. This list is neither complete nor exhaustive, since there is no "best function model" available (Vermaas and Eckert, 2013). The three approaches are selected because they each take a different approach to how function can be expressed and how it would be connected to the product geometry model fulfilling the modelled functions.

The **Function-Behaviour-Structure** (FBS) model as described by (Gero, 1990) focuses on the relations and processes between the different product aspects function – as in "what is it supposed to do" – behaviour – "how does it perform" – and structure – "how is it composed" and "how does it look".

A function model is used to capture the identified functions of a product and map them towards the product's behaviour or structure. Commonly it is distinguished between the product's function and its behaviour. The behaviour is how the product actually performs in interaction with the environment, while the function is the intended action which serves a purpose (Roozenburg and Eekels, 1995). The relations between the product's function, behaviour and structure are illustrated in the Function-Behaviour-Structure framework (FBS) as shown in Figure 2.7.
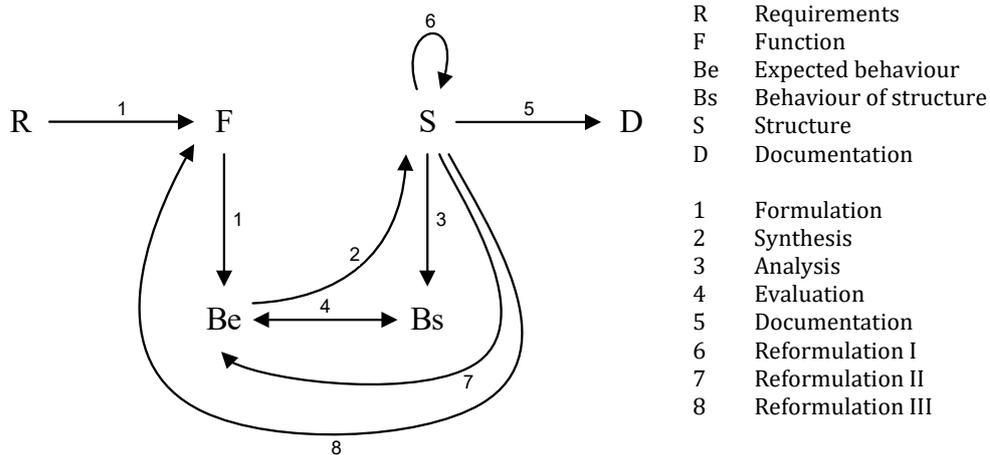
Figure 2.7 FBS ontology of designing, redrawn as found in (Milovanovic and Gero, 2018), based on (Gero and Kannengiesser, 2004) and (Gero, 1990)

The abstract process of translating requirements to functions, and then from these to the expected behaviour is illustrated as transformation from *R* to *F* to *Be*. The actual design process is the synthesis of creating an artefact, the structure (*S*), which is supposed to show the same actual behaviour (*Bs*) than the expected behaviour (*Be*). To see if the design actually behaves as expected, *Be* needs to be evaluated in respect to *Be*. To know about *Bs* the structure needs to be analysed. For this, a sufficiently matured representation of the structure *S* is needed – most commonly in the form of a CAD model.

**Enhanced Function-Means** (EF-M) modelling is a modelling approach based on the Theory of Technical Systems by (Hubka and Eder, 1988), which states that *"the primary functions of a machine system are supported by a hierarchy of subordinate functions, which are determined by the chosen means"*. Tjalve (1976) and Andreasen (1980) developed a function modelling method that allows to create Function-Means trees alternating between a Functional Requirement (FR) and its Design Solution (DS) with subsequent FR which are required by the chosen DS.



FR Functional Requirement
DS Design Solution
iw Interacts with
C Constraint
isb Is solved by
rf Requires function
ipmb Is partially met by
icb Is constrained by
iib Is influenced by

Figure 2.8 Enhanced Function-Means tree syntax
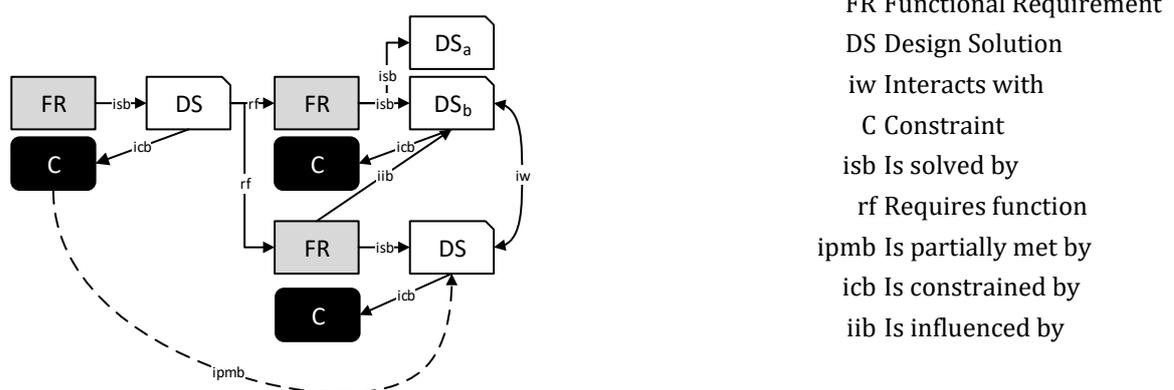
In further development by (Schachinger and Johannesson, 2000) the method was enhanced through the addition of modelling constraints, limiting the possible design solutions, and connections between solutions, either partially meeting higher level FR or interactions between same-level FR. The modelling syntax is illustrated in Figure 2.8, which also shows the modelling

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of alternative solutions for one DS. While enforcing the axiom of independence by only allowing one solution for each function, which apparently defines "a good design" (Suh, 1990), EF-M allows to model alternative solutions in the same tree, therefore providing the means for both platform modelling (Raudberget *et al.*, 2015) as well as supporting SBCE (Levandowski, Raudberget and Johannesson, 2014).

Configurable Components Modelling (CCM) enables to structure an EF-M tree into modules, allowing for a better overview but also the ability to exchange alternative modules to re-combine the concept into different instantiations, which fulfil the same top-level functions but with different solutions (Claesson, 2006). This ability makes EF-M, together with CCM, a method to assist in the exploration of function and solution oriented search spaces.

The **Contact and Channel Approach**[3] (CCA) defines a product through surfaces, their interaction and the structure between those surfaces. The approach is based on "Wirkflächenpaare & Leitstützstrukturen" by (Albers and Matthiesen, 2002). Working Surface Pairs (German "Wirkflächenpaare") (WSP) are defined between different elements of the product or its environment and are connected via Channel and Support Structures (German "Leitstützstrukturen") (CSS), together forming a "Wirk-Net"[4] (Albers and Sadowski, 2014). Figure 2.9 shows the WPS between a self-drilling screw and the wall on one side, and the drill bit on the other. The WSP define the use case, and therefore the function the product fulfils.
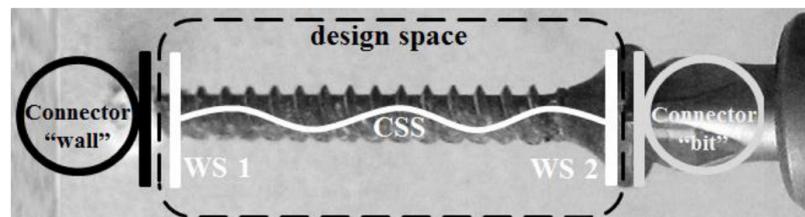


Figure 2.9 CCA model of a self-drilling screw and its environment, showing the CSS and working surface pairs (WS) from (Albers and Sadowski, 2014)

CCA is mainly used to generate an extended understanding of the functioning of a product through identification of the Wirk-Nets (Albers and Sadowski, 2014). From there on, the method can be used to analyse and improve the function-structure relationships of existing products.

## 2.3  Knowledge Based Engineering

As stated above, product development includes often an exploration of a design space – covering different search spaces with different methods and approaches. An example for a traditional approach are morphological boxes, which aim to cover different dimensions in the search space through the combination of multiple technological principles (Pahl *et al.*, 2013). And while these methods as well prescribe the simulation and analysis of each concept, they do not provide any

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[3] Also: Contact and Channel Method (CCM), but referred to here as CCA to avoid confusion with the Configurable Component Modeller, CCM

[4] From German "Wirkung" meaning effect

aid in modelling a large number of concepts – the decision of which design to pursue needs to be done based on the abstract descriptions found in the matrix.

For the generation of multiple product representations Knowledge Based Engineering (KBE) aims to make use of automation processes. The overall aim of KBE is to generate knowledge about a product variety (Verhagen *et al.*, 2012), and be able to reuse it. To achieve this, computer models of the product are generated in such a fashion that they can be modified through rule-based systems which allows for variations of different degree. The different models are used for simulation and analysis to gain an understanding, i.e. knowledge, about the products' behaviour in relation to its design parameters. One approach to this is presented by Sandberg et al. (2011), who propose a so-called *master-model* from which design instantiations can be generated. The master-model is a parameterised CAD model, which can be instantiated through recorded macros and programming scripts accessible from a GUI. The instantiated models are automatically subjected to an analysis tool-chain.

Closely related[5] to KBE is **Design Automation** (DA), which focuses on the creation of flexible CAD models. The easiest approach to this is the automated instantiation of parameterized CAD models, as described above, where geometrical dimensions in the CAD model can be governed through an input file. Other approaches, such as by Amadori et al. (2012) use high fidelity CAD models based on a part library, similar to La Rocca and Tooren (2006). Both create e.g. alternative airplane geometries based on CAD scripting languages. Shea, Aish and Gourtovaia (2005) use similar advanced CAD models for the automatic creation of alternative stadium roofs. In a not CAD based approach, Helms and Shea (Helms and Shea, 2012) explore alternative solutions principles on a more abstract level, such as the combination of strut and joint elements into bike-frames. This appraoch covers a solution-oriented search space instead of the purely geometrical-modular or geometrical-dimensional approaches in most KBE applications.

Mejía-Gutiérrez and Carvajal-Arango (2017) bring the design automation process one step further by adding a connection to the products logical and functional structure, and derive and entire synthesis and analysis framework from that. While the approach shows a clear connection between different product models, it does lack the design space exploration approach, i.e. generating alternative solutions. However, especially in the embodiment of CATIA v6 in one single software suite, their example shows a gap-less product knowledge chain over multiple modelling domains.

**Multi-disciplinary analysis**

Multi-disciplinary analysis (MDA) is a practical application of KBE and DA is for the purpose of analysing a range of variants. In the context of design space exploration, the cost of creating models for each different alternative concept grows with the number of parameters under investigation. To counter this effect, and keep the computational effort to a minimum, it is possible to create a *metamodel* from analysis data. This is, however, not a product model, but the set of

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[5] Some authors, such as Van Der Velden et al (2012) call DA a sub-discipline of KBE

results from the behaviour simulation of multiple product variants. Using statistical analysis, the results for parametric combinations that have not been simulated can be estimated (Simpson *et al.*, 2001).

To be able to actually cover a large part of the design space, different "space filling" methods can be applied. Often these are Design of Experiment (DoE) sampling methods of the design parameters. Pronzato and Müller (2012) give an overview over such methods.

In the progress of this work variations of a MDA framework have been applied in multiple projects and studies. The framework is based on the Engineering Workbench (EWB) as described by Heikkinen and Müller (2015), which is largely similar to the master-model approach by Sandberg et al (2011) described above. Although EWB explicitly describes the version of this framework which is used at the case-company, and not all applications in this research use the exact same setup, for the sake of easy identification the MDA frameworks used in this research are referred to as EWB in this thesis. The framework, illustrated in Figure 2.10, consists of a Python script which is capable of generating a bandwidth of alternative geometries based on a Siemens NX master model. The dimensions of the alternative geometries are collected from a spreadsheet and consecutively applied.
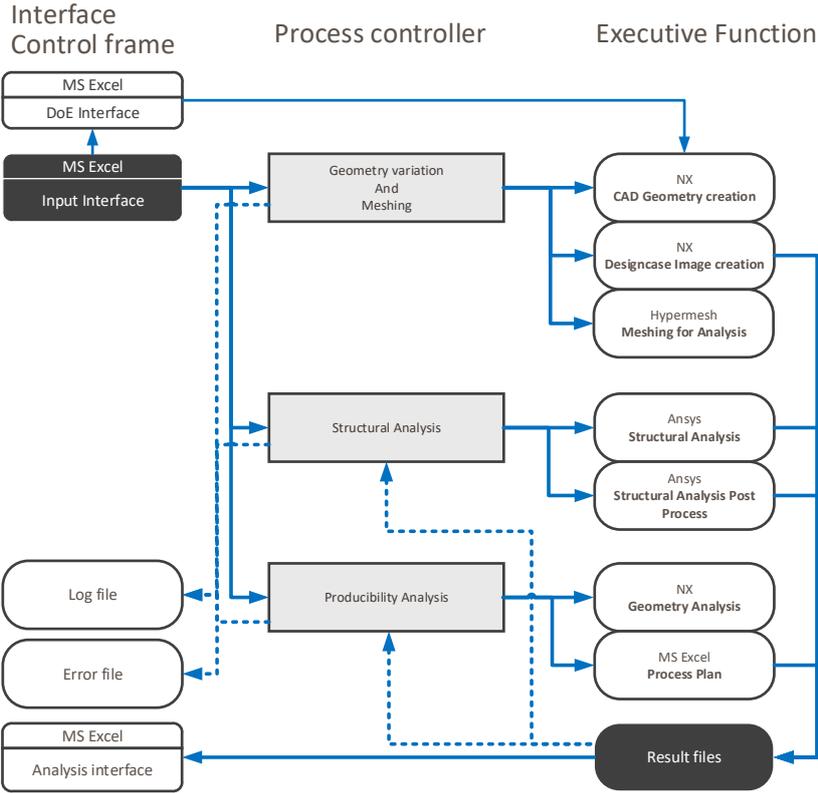


Figure 2.10 Engineering Workbench (EWB) working principles from (Heikkinen and Müller, 2015). In different studies mentioned in this thesis different ranges of analysis have been applied to a varying extent.

**Multi-disciplinary optimisation**

To explore a design space efficiently, it helps to look into different value dimensions at the same time. Furthermore, it may be that different simulations in different disciplines rely on each other's

results – such as the mechanical loads of an airplane wing are highly dependent on the aerodynamic forces acting on it. This connectivity between the different disciplines can lead to problems when trying to analyse, or even optimize the design for a specific result. This coordination of disciplines and simulation results is one of the main challenges of Multi-disciplinary Optimisation (MDO) (Martins and Lambe, 2013).

The other challenge is the optimisation goal – while it is comparably easy to optimise a product towards one single goal, say engine performance, the host of stakeholders requires different and often contradicting optima. For example, an aircraft has to be optimised for least drag, high stability, low weight, high thrust and minimum fuel consumption. They may result in contradicting design parameters, e.g. when optimising for low weight, stability and thrust decline, and vice versa. This conundrum can be approached by either weighing the different goals respectively and from this formulate a single goal through summing up all goals into a scalar (Andersson, 2000). Another way to balance these different goals is Value Driven Development, as explained above.

# 3 Research Approach

*Explaining how the data for this research work has been gathered and analysed.*

An estimated 85% of product development projects encounter problems in cost, time management or simply not functioning as intended – a problem that can be solved by studying and improving the design process (Ullman, 2003). Design research (DR) has the goal to generate knowledge about the design process as such, but also to improve said design process (Eckert, Clarkson and Stacey, 2003). Therefore, design research needs to be distinguished from "natural sciences", since it studies "the artificial" – not processes observed in environment, but how to create new artefacts (Simon, 1996).

Conclusively, this research pursues two different goals: create understanding for the phenomena as well as improve them (Eckert, Clarkson and Stacey, 2003). In this dual task, DR also tries to serve two different masters: providing reportable results for the academic community, as well as provide reliable tools and methods for the industrial practitioners. Therefore, it is also subject to two types of validation: while the academic results need to be valid in terms of methodical data collection and evaluation, the industrial side requires the methods and tools that are developed in the course of DR to be powerful, reliable and validated (Eckert, Clarkson and Stacey, 2003).

## 3.1 Research framework

The different studies which lead to this publication are connected in a framework which is based on the *Design Research Methodology* (DRM) by Blessing and Chakrabarti (2002). The framweork follows the pattern criteria definition - descriptive study 1 (DS1) – prescriptive study (PS) – descriptive study 2 (DS2) as illustrated in Figure 3.1. How each of the appended papers contributed to the respective studies is shown in Table 2.
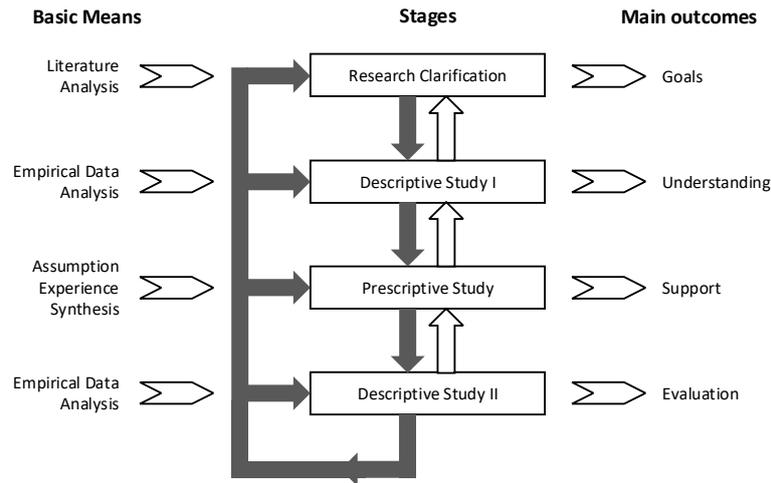
Figure 3.1 DRM framework, reproduced after Blessing and Chakrabarti (2009)

The aim of the study is to improve the product development process, in particular design space exploration. Therefore, the results of this research are supposed to enable the design of better products through a more efficient and effective exploration of alternative design solutions. The quality "better products" is a difficult criteria, since the definition of what a better product is differs according to sources – e.g. Suh (1990) defines the best product as the one satisfying the two axioms of independence of function and solution as well as least information content. VDD however defines the best design based on a weighing of product qualities relative to stakeholder interests (Isaksson *et al.*, 2013). Furthermore, the development of a better product can always be the result of multiple factors and the overall quality of a single product is therefore insufficient as a criterion for the impact of one single method in the product development process.

Table 2 DRM phases in appended papers

| | Criteria Definition | DS1 | PS | DS2 |
|---|---|---|---|---|
| Paper A | | | | |
| Paper B | | | | |
| Paper C | | | | |
| Paper D | | | | |

The following quantifiable success criteria have been set based on literature research and results from mainly paper A with contributions from papers C and D, as is illustrated in Table 2:

- Number of  alternative solutions generated
- Number of alternative solutions evaluated
- Diversity of alternative solutions
- Diversity of chosen solution from legacy design

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These criteria will be applied for the development of a DSE method which is based on the results and conclusions presented in this thesis.

The overall progress of the research project has concluded the phase *descriptive study 1*, observing the as-is situation in industry and as described in literature, and therefrom deriving the need for the above described research questions. All appended papers have contributed to this phase to different extend, as can be seen in Table 2. The as-is state of product development has been analysed through in an action research approach, i.e. through the participation in collaborative projects with practitioners (Avison *et al.*, 1999). Furthermore, interviews with practitioners, as well as workshops and through observation in industrial-academic demonstrator projects have contributed to DS1. Based on the results from these interviews and observations, an image of the current state of design space exploration in the context of development of complex engineering products has been gained.

Building on the results from DS1, the prescriptive study (PS) is concerned with the development of a method that supports the aim of this research – to improve product development through better design space exploration. At the current point of research, the requirements and an initial concept for this method have been established, mainly published in papers C and D. The method will further be developed in at least two iterations, where the initial concept will be implemented in a prototype software tool and tested in cooperation with practitioners. The use of such prototypes for academic-industrial collaboration research is suggested by Isaksson (2016). Based on the results of these prototype tests, the method will be refined, and an improved method and tool will be tested in further workshops in the same contexts. This is aligned with the spiral model by Eckert, Clarkson and Stacey (2003) – the questions on how to implement a tool is as important as the question of what kind of tools to implement.

As a final step, in the descriptive study 2 (DS2), the fully developed method will be implemented in an industrial product development context and evaluated according to the criteria that have been established above. Interviews with the participating practitioners will conclude this study.

## 3.2  Research context

The research which has contributed to this thesis has been performed in four different research projects. Each research project has contributed to different stages of the research. Based on the spiral model by Eckert, Clarkson and Stacey (2003), these stages are oriented on the goal to develop insight into the product development process and its challenges as well as provide methods or tool towards its improvement. How the four projects as well as the appended papers are related to these phases is illustrated in Figure 3.2. The main methods used for data acquisition used in all projects are interviews, demonstrator prototypes, literature research and workshop throughout different phases of the projects. The methods and their use are explained in detail in Chapter 3.3.
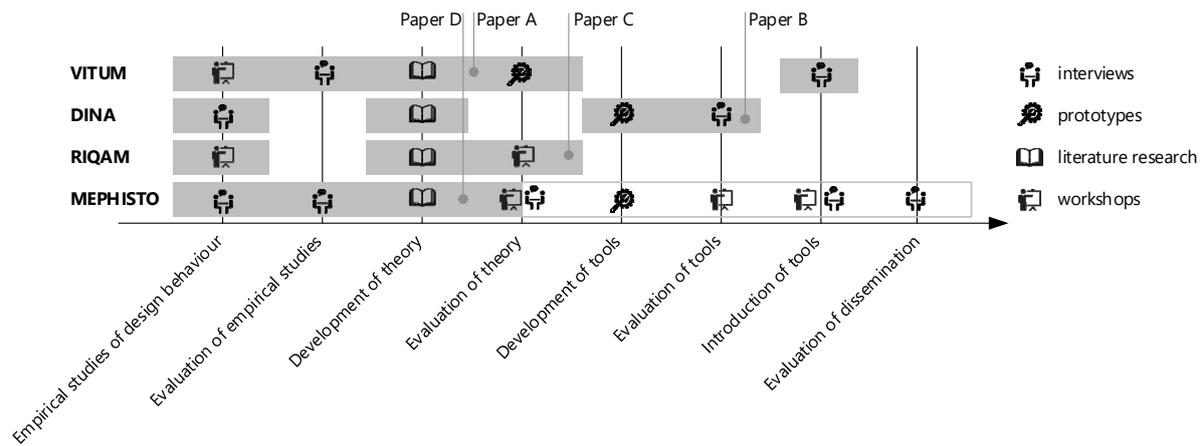
Figure 3.2 Research studies and main methods over the research phases according to Eckert, Clarkson and Stacey (2003)

## VITUM

The project "Virtuell Turbinmoduldemonstrator" – virtual turbine module demonstrator, VITUM – is a collaboration project between academia and industrial partners. Over the course of 18 months the development of alternative designs for a turbine rear assembly was studied. The project is a simulator project aiming to validate technologies and product development methods. A majority of the research work was performed in workshops with the industrial partners from the aerospace industry. Furthermore interviews with the involved practitioners were used to gather insight. A prototype framework of the developed methodology was created, and analysed in interviews. This project lead to Paper A is a direct outcome of this project.

## DINA

A demonstrator project for the abilities of additive manufacturing and lifecycle perspectives, the project Digitalisation IN Additive manufacturing (DINA) was performed in collaboration with industrial partners and research institutes. The development of a virtual demonstrator tool was based on a support bracket for a civil aircraft engine. Based on interviews and literature, the main contribution to the project was the development of a demonstrator prototype, which was evaluated with stakeholders from academia, industry and society. The project went on for 12 months, and the main results are published in paper B.

## RIQAM

The project "Radical Innovation and Qualification using Additive Manufacturing" (RIQAM) is a project aiming at the validation for additive manufacturing technologies for the aerospace industry. Therefore, three Swedish aerospace companies participated in the project with individual cases, and were present in workshops and for interviews. The main contribution was a method for re-design of existing products to the changed requirements of AM. Paper C is a result of the collaboration in this project.

**MEPHISTO**

This project, Modelling for Early PHase Investigation into alternative Systematic and Technological Options (MEPHISTO), is an ongoing collaboration between the author's university and a Swedish aerospace company with the aim to improve the modelling of alternative designs for enhanced design space exploration. The author is the main researcher in this project. The project is currently phasing out the descriptive studies and starting with the development phase for a demonstrator tool. The research performed in this project so far resulted in paper D, however, the other projects' results had significant influence on this paper.

## 3.3 Data collection

The research so far has been executed in close collaboration with industrial practitioners. Therefore, an action research approach, i.e. research results are gathered through collaboration with practitioners (Avison *et al.*, 1999), was chosen as a method to gather data. This included the observation of practitioners' behaviour in their daily work routine, as well as explicit data capturing activities.

**Workshops**

The majority of data for paper A, B and C was captured through workshops. All publications are the result of industry-academic collaboration projects, where the close collaboration with the industrial partners allowed for a deep insight into the work process and perceptions. Most workshops were designed with a design or engineering task, which was to be performed by the present industry and academia representatives alike. Observations that deemed special to the researchers leading the workshops were captured, as well as the results of the workshop tasks. The capturing included notes and pictures. The data sampling was cumulative, i.e. consecutive observations build onto each other to create a holistic image (Denscombe, 2010).

**Interviews**

During the workshops as well as afterwards for the refining of specific points, semi-structured interviews with practitioners were performed. These interviews were 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 transcribed and analysed respective to the needs of each study.

**Prototypes**

To be able to communicate ideas and concepts towards industrial and academic research partners, different types of prototypes were used to communicate ideas of approaches or to test such approaches, methods or tools, as is recommended by Isaksson (2016). These prototypes are software prototypes of different grades of functionality. Paper B used a web-based mock-up of the potential tool-chain with simulated functionality. The workshops in Paper C used the suggested method in a pen-and-paper basis in several workshops as a method of data-gathering as well as for validation purposes.

## 3.4  Validation

This work is situated in the field of design research (DR), therefore it pursues two different goals: create understanding for the phenomena as well as improve them (Eckert, Clarkson and Stacey, 2003). In this dual task, design research also tries to serve two different masters: providing reportable results for the academic community, as well as provide reliable tools and methods for the industrial practitioners.  Therefore, it is also subject to two types of validation: while the academic results need to be valid in terms of methodical data collection and evaluation, the industrial side requires the methods and tools that are developed in the course of DR to be powerful, reliable and validated (Eckert, Clarkson and Stacey, 2003).

Below, the research activities and studies in this research are inspected in the context of academic validation. The validation of the method for industrial use is included in methodology through the inclusion of DS2, which assesses the actual impact of the method on the research subject. Furthermore, the usability and applicability evaluated and optimised in PS.4 to PS.9 in the term of recurrent testing and refinement.

**Academic validation**

The results obtained in the descriptive studies are used to develop a hypothesis of the how the current state of the art and working practices in industry look. This is done by concluding from a few observations to an image of the whole, i.e. through inductive reasoning (Williamson and Bow, 2002). To be able to accept the hypothesis about the current state of the art in industry as true, it needs to be validated through deductive reasoning. Therefore, more data, which is aimed at disproving the hypothesis, needs to be collected. Only if the results from this validation study do not contradict the initial hypothesis can it be accepted as valid. Additional interviews with engineers and developers at a case company have been performed for this purpose, however, the study has not been published yet. But, as stated by Eckert, Clarkson and Stacey (2003), in cannot be expected from a single PhD project to "achieve[…] the usable results we aim for". Therefore, available results from other studies are used as data source, in the form of literature research, where other case studies in industry are taken to support the claim about the state of the art. Examples for these studies are (Ullman, Stauffer and Dietterich, 1987; Schön and Wiggins, 1992; Albers *et al.*, 2008; Kurtoglu, Campbell and Linsey, 2009; Eckert *et al.*, 2012).

**Industrial validation**

The developed method will be tested in different settings to test it for usability and robustness. The activities will be set towards the end of the prescriptive study will be. The validation process will be aligned to product development principles, such as establishing requirements for the method and testing towards their fulfilment as is illustrated by e.g. Pahl et al. (2013). Demonstrator prototypes as suggested by (Isaksson, 2016) will be used to gather industrial feedback. However, the development of a software based engineering support tool in the scope of a research thesis cannot provide a tool that can compete with industrially developed engineering tools. This might provide challenges in separating the evaluation results of the method from the evaluation of the tool.

# 4 Results

*The outcome of the research, as presented in the appended papers.*

The results section of this work is composed of the results from the appended papers. The findings from those works are presented individually and the core results are presented in relation to the two research questions. The appended papers are:

Paper A  Isaksson, O., Bertoni, A., Levandowski, C. E., **Müller, J. R.**, Wiklund, D. and Johannesson, H. (2016). *Virtual contextual validation of technologies and methods for product development*, in Proceedings of International Design Conference, DESIGN, pp. 669–678.

Paper B  **Müller, J. R.**, Panarotto, M., Malmqvist, J., & Isaksson, O. (2018). *Lifecycle design and management of additive manufacturing technologies*, in Procedia Manufacturing, 19(2018), 135–142

Paper C  Borgue, O., **Müller, J. R.**, Panarotto, M., & Isaksson, O. (2018). *Function modelling and constraints replacement for additive manufacturing in satellite component design*, in Proceedings of NordDesign 2018.

Paper D  **Müller, J. R.**, Isaksson, O., Landahl, J., Raja, V., Panarotto, M., Levandowski, C. E. and Raudberget, D. (2018). *Enhanced function-means modelling supporting design space exploration*, in Artificial Intelligence for Engineering Design and Manufacturing, (submitted)

## 4.1 Paper A: Virtual contextual validation of technologies and methods for product development

This paper reports from the VITUM project. Multiple alternative options for a turbine rear assembly are to be developed and evaluated. Different functions and solutions are developed in different workshops, and through the project a concept development an evaluation method is developed.

The problem approached in this paper is that in the aim to develop new and better products, new technologies and product development methodologies need to be developed. However, there is a challenge in introducing these into products and processes, since the validation commonly

requires physical demonstrators. Such physical demonstrators and prototypes are expensive, and can therefore not be built for a large number of design alternatives. This limits the ability to explore alternative novel technologies, and reduces the chances of novel products to be implemented or even evaluated.

A virtual demonstrator is suggested to encounter this. Explained using the TRL scale, the demonstrator aims to move innovations from "functional demonstrator" (TRL3) via "laboratory demonstrators" (TRL4) to a "first validation in relevant environment" (TRL5). The positioning of the virtual demonstrator in relation to the TRL is shown in Figure 4.1 for both products and product development technologies.
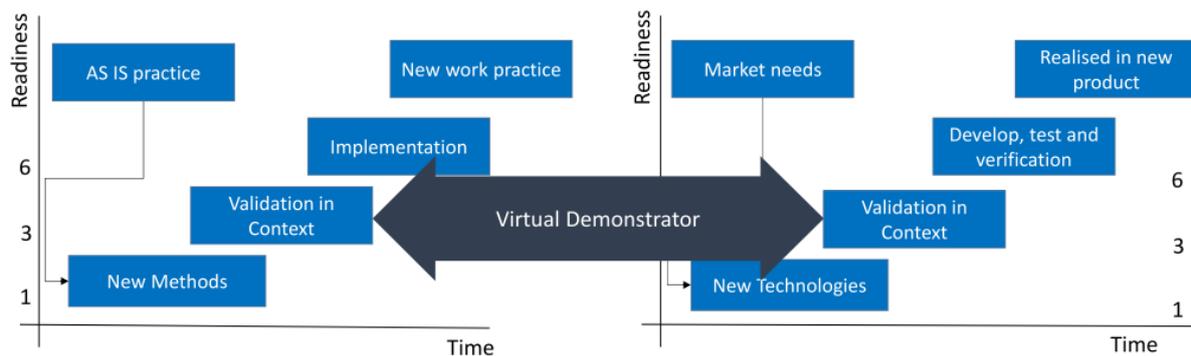


Figure 4.1 Virtual demonstrator to validate context of methods and technologies, from (Isaksson *et al.*, 2016)

The problem posed recognises the need for a design space exploration method which builds on legacy designs, and enables the inclusion of novel sub-solutions into an existing modelling environment. Furthermore, the need to compare solutions of different levels of maturity.

The demonstrator prescribes a series of activities, illustrated in **Error! Reference source not found.**. Stakeholder needs are captured in an EVOKE matrix. Existing solutions and functions are captured in an EF-M model, which is capable to model the different abstraction levels of the function-solution structure. New functions as well as solutions on different levels were captured in multiple workshops, and added to the function model. After the first workshops, over 100 concepts consisting of different solutions with different levels of maturity were collected in the EF-M model.

Figure 4.2 VITUM working process

The engineering characteristics of the existing solutions are captured and stored in the EF-M model and can be retrieved from there for evaluation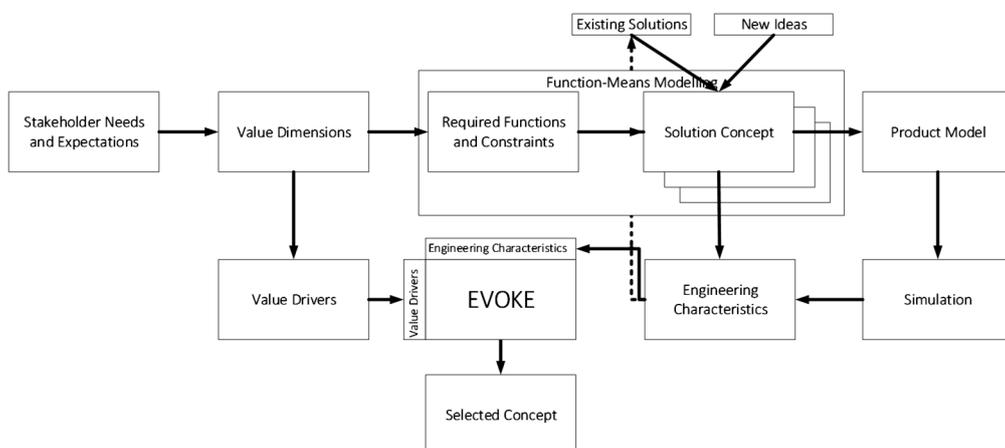 of the legacy designs. However, several important engineering characteristics of the novel concepts and designs require simulation based on 3D geometry models, such as thermal expansion of the cone and the respective impact on the cone-TRS interface as illustrated in Figure 4.3. The effort required for the development of the different CAD models, which are needed for the simulations, was so high that only three out of over 100 different concepts could be evaluated. Although it was attempted, the effort of creating more models could not be reduced through the application of a parameterised CAD model in the form of EWB, since the geometrical variances of the different concepts were too large. Furthermore, the concepts showed variance in different sub-solutions which would have required the substitution of specific sub-sections of the CAD models. However, these sections did not at all coincide with the geometric elements the CAD models were constructed from, hence an automation of this process could not be achieved.

The EF-M function model is used to capture the different alternative technologies and configurations that are developed throughout the exploration process. It captures the existing design variants and provides a platform for multi-disciplinary development teams to expand it. It is connected to the
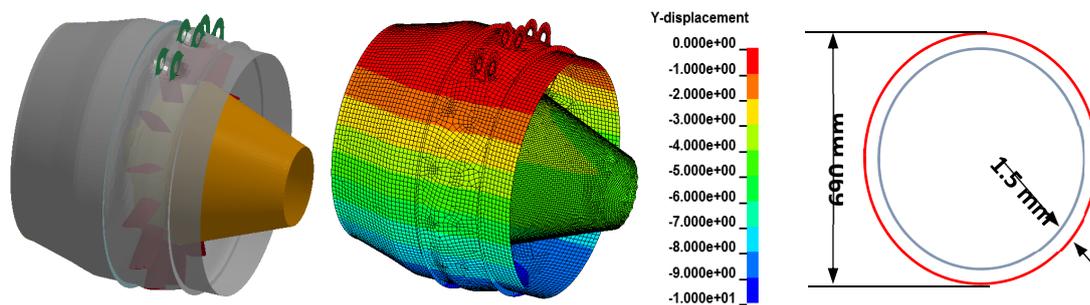


Figure 4.3  theoretical gap between TRS and cone due to thermal expansion mismatch CMC – Steel at 650°, simulations from the VITUM project performed by Swerea IWF.

The project illustrated the challenges of generating knowledge about novel design alternatives, especially when they differ in function and solution principles from the legacy design. As the main hinder in this case was the cost of generating appropriate CAD models identified. On the other hand, the project illustrates the opportunities of using a function model, in this case EF-M, to capture different solutions and alternative functions on a higher abstraction level. EF-M models also provide a basis for the capturing of existing product knowledge in a solution-specific system. Furthermore, the use of a VDD as a common ground to compare concepts of different working principles and levels of maturity was beneficial to the design space exploration process.

## 4.2 Paper B: Lifecycle design and management of additive manufacturing technologies

Additive Manufacturing (AM) is a novel technology that is about to be introduced into aerospace product development. While AM brings the possibility of an increased design freedom and the chance for detailed customization, the production of individually different products requires individual product modelling, analysis and evaluation. Furthermore, to enable an effective customization of products, a concrete mapping of customer requirements to design parameters is necessary.

This publication presents a through-life information management approach for products developed for AM. The product, an attachment point for a civil aircraft engine, is to be adapted to changing stakeholder requirements and use-cases, in order to make use of the direct-manufacturing capabilities of AM. To enable this, the product's functions and respective solutions, including alternatives, are modelled in EF-M. A value model captures the high-level needs and is connected to the functions and solutions in the EF-M model. Customers can configure specific parameters of the product such as interface dimensions, and the respective values are connected to a geometry configurator through the function model. A new dataset is created for each configuration, and furthermore for each product that goes into production, as is illustrated in Figure 4.4. In the idealised demonstrator, the entire manufacturing process for each product is recorded and can be monitored.
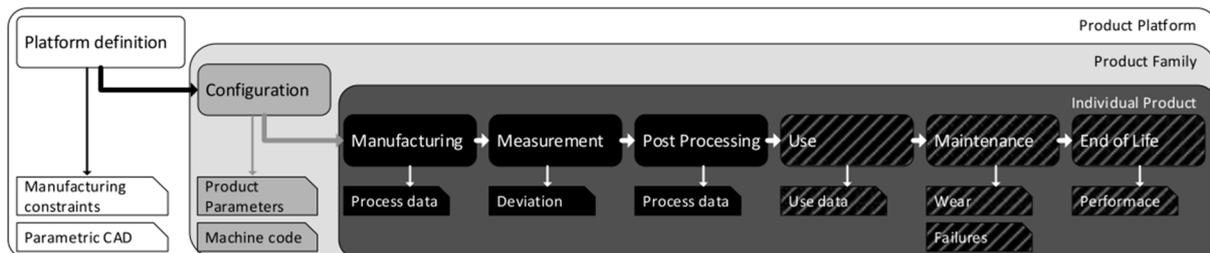


Figure 4.4 Process- and data flow in the demonstrator. Hatched elements have not been realised due to time and resource constraints. From (Müller, Panarotto, *et al.*, 2018)

The work in this paper contributes mainly to research question 2, what enablers are identified for an improved design space exploration. Furthermore it shows that there are design parameters, such as the through-life aspect, which increase the design space even further than originally expected. This raises new challenges towards product development in terms of required product functions as well as in the simulation of long-term product behaviour and multiple life phases. The presented data collection and association to individual product instantiations allows for an understanding and learning about these new design dimensions.

Beyond that, the study and resulting paper enhance the need for a model of higher abstraction to capture both design intend of features as well as their contribution towards the product's value dimensions and stakeholder needs. A customisation of product's to stakeholder's needs is only possible if designers know which feature of the product fulfils this need, and to which degree and quality. Beyond the customisation, this need is given for all product development – a sub-solutions

value can only be assessed when its contribution to the overall value of the product is known. The introduction of both a value and a function model which were linked to each other enabled this to the degree of a demonstrator. However, the implementation and validation require further work.

## 4.3 Paper C: Function modelling and constraints replacement for additive manufacturing in satellite component design

The redesign of existing product for the novel manufacturing technology Additive Manufacturing (AM) often focuses only on manufacturing aspects while neglecting the chances and opportunities AM can bring to the entire product geometry. The design freedom and material choices allow to maintain the original functionality while reducing weight and even potentially improving performance parameters. To enable designers to make use of this new design freedom, a re-design methodology that builds on function modelling is proposed.
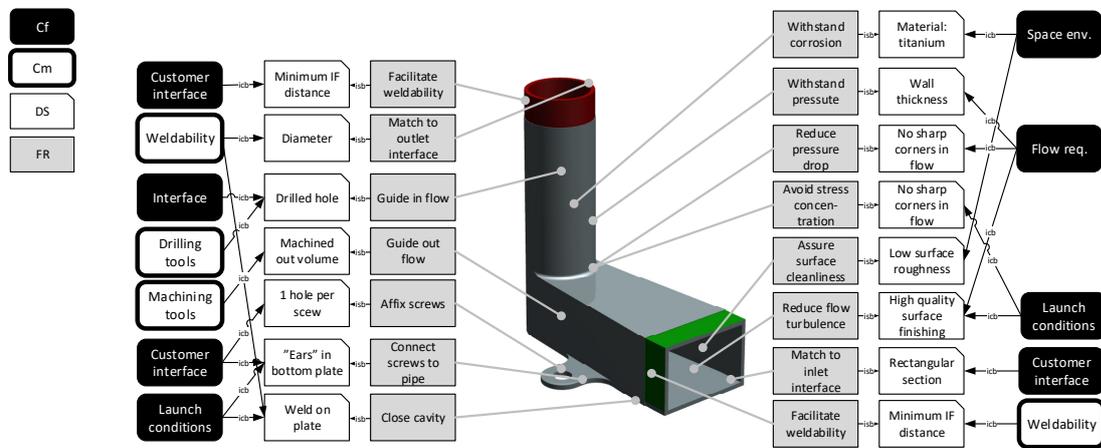


Figure 4.5 Original part geometry and functional decomposition, from (Borgue *et al.*, 2018)
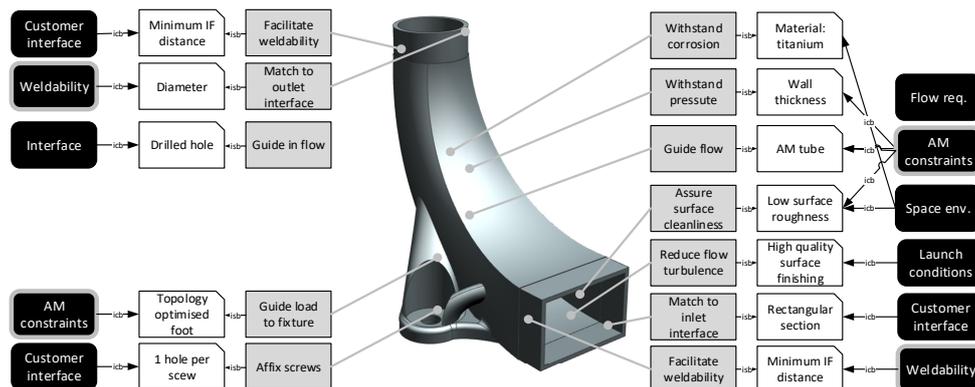


Figure 4.6 Redesigned part and associated function model, from (Borgue *et al.*, 2018)

The product that is to be redesigned is first decomposed into its functional structure. This structure is represented through an EF-M model which is built bottom-up from the design features of the original product. In addition to the identified functionality, and where it is located on the geometry, constraints on said geometry are identified. These constraints are sorted into

manufacturing and function based constraints. Through the change of manufacturing method, certain constraints can be released and the affected geometry is free for re-design under DfAM constraints.

This is illustrated in a case study in cooperation with several aerospace companies. Based on the input from multiple workshops a demonstrator product has been generated. The original demonstrator product together with the identified functions is illustrated in Figure 4.5, while the redesigned geometry and the associated functions are shown in **Error! Reference source not found.**.

The study has shown that the existing geometry of a product can limit the potential design freedom of the redesign process. The developers originally adhered closely to the existing shapes and ideas, be it because they are well-proven or because it is simply easier to re-use existing designs. This is a limiting factor that contributes to a reduction of the search space to designs that are closely related to the original one.

To break out of these limitations, the suggested use of EF-M as product model allows for a geometry-independent view on the design space. The modelling and removal of constraints highlights which areas can be re-designed under new manufacturing constraints, and which geometric features need to remain due to their functional nature. The contribution to distinguish between function and manufacturing related constraints enables a clear overview over the impact of specific constraints and helps in the redesign.

While the method has been applied in this case to enable redesign for AM, the functional decomposition focusing on actual geometrical features has shown to allow for an improved product understanding as well as providing a description of the design space and the available freedom and constraints. However, the method requires refinement in the detailed association between geometrical and functional domain.

## 4.4 Paper D: Function-Means Modelling to Support Reverse Engineering and Innovation

This publication introduces Enhanced Function-Means modelling as a facilitator for extended design space exploration. While DSE has already been explored and applied by other researchers, this has mainly happened through the variation of CAD models. When introducing novel design solutions into an existing CAD model, the CAD model proves to be too rigid in its modelling nature to accommodate a variety of new solutions. In applied product development, however, the common practice is to build onto existing designs. Function models, on the other hand, have rarely been used as the basis for DSE approaches – but provide the flexibility to introduce novel solutions at any abstraction level.

A potential solution is presented through the use of a function model in the form of EF-M as a facilitator for re-design. Based on a function modelling benchmark product, a glue gun, the prescriptive study shows how to redesign a product while both building on existing designs and expanding into radical innovations. The existing product is functionally is analysed in its sections,

and a novel requirement is introduced. Through the use of the EF-M model, the re-design of the function structure enables a change only in the functionally affected sections.

To base the presented methodology on a theoretical basis, a comprehensive analysis of EF-M as a function-modelling method is provided. It concludes that while EF-M can be a basis for systematic redesign of products as well as the enable the initial analysis of systemic values, certain challenges in the approach have been identified.

The proposed methodology is illustrated in Figure 4.7. The approach suggests function modelling (in blue) as a backbone for design space exploration, where the ease of adaptability of function models is a supposed to enable the exploration of a larger area of the design space, which is illustrated by the full circle in the right hand figure. The two views in Figure 4.7 can be seen as the same figure, where the left hand view is a cross-section A-C in the right hand view. The existing product design, in the form of a geometry model (left hand view, bright orange) is decomposed in process (1) into a function model of the same design, the bright blue half-circle. While smaller area of the function model illustrates a lesser amount of captured product knowledge, it includes systemic knowledge, illustrated above the x-axis, which is not present in the geometry model. Process (2) depicts the design process, where new solutions and concepts are innovated – the function model is extended into a new design dimension (C) in the right view. To be able to understand and analyse the new design, it needs to be embodied (3) into a new CAD model, dark orange.
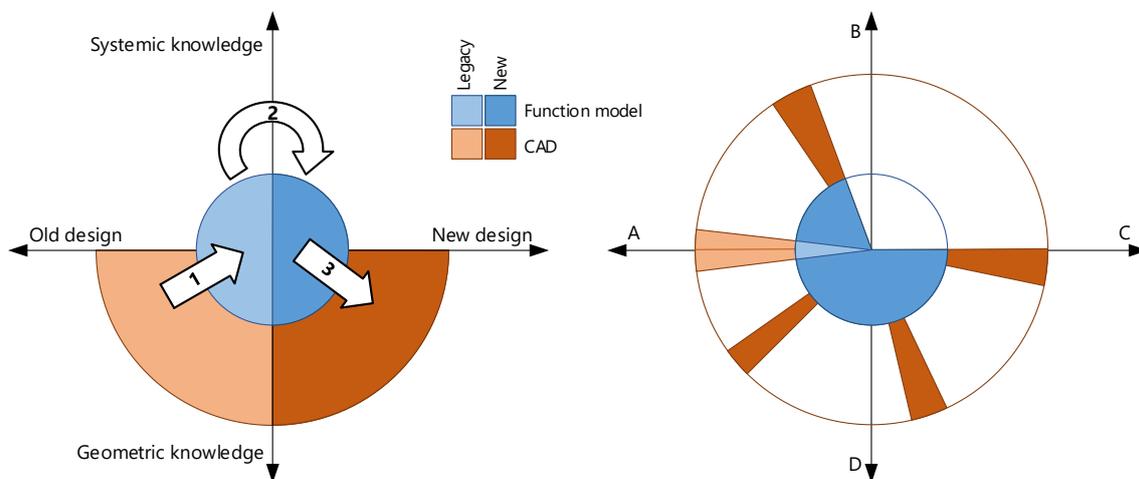


Figure 4.7 Design space exploration supported through function modelling, from (Müller, Isaksson, *et al.*, 2018). The right hand figure, the following processes are illustrated: (1) functional decomposition, (2) design and (3) embodiment. In the right hand figure, A, B, C and D represent different dimensions of the design space. The left hand figure represents a section through A-C in the right hand figure.

The right hand view illustrates how much more of the design space can be covered this way. The bright orange slice on the left, a projection of the original CAD model in the left hand illustration, illustrates the search space which would be available by only modifying the original CAD model. However, by using a function model as an intermediate, the approach can facilitate a coverage of a much larger search space. Although even the function model may not cover the entire search space, as the DSE is still limited by human capacities. This is illustrated in an incomplete coverage

of the design space circle in blue. The orange beams illustrate design ideas which have been identified as potentially promising on the functional domain, and then proceeded with CAD models for further exploration.

## 4.5 Key results and findings

The challenges addressed in this research are the limitations in coverage of the design space in the product development process. As a results, it has been found that the search for new solutions, and subsequently the solutions that are procured from these explorations, is often undertaken very close to the existing design. In all appended papers, a function modelling-based method is suggested to enlarge the search space for DSE. The following is a summary of the findings which is sorted into the three design space exploration phases: definition, population and analysis.

**Definition of design space boundaries**

According to literature, the definition of the design space is necessary to be able to define a proper search space (Suh, 1990; Woodbury, 1991). Therefore, identifying the boundaries and design dimensions is a crucial step in design space exploration. In the observed product development practices a lack of methods for the definition and description of the design space has been observed. This is not to be confused with the capturing of requirements, which are a corner stone of product development (Pahl *et al.*, 2013). However, an observation made in each research project is that the requirements are often captured as solution specific product properties. The "function", i.e. the intended behaviour of a product which ultimately generates the value for the user, is not captured as such, but merely performance parameters of a pre-determined solution. As a result, e.g. a TRS is not developed with the idea to fulfil the function to guide the airstream and carry the engine load. Instead, an existing spoke-wheel-structure is adjusted to fulfil requirements of specific temperature- and structural loads. As a consequence, the original design is optimised and adapted to fulfil the new requirements, often neglecting more radical solutions, as has been stated in papers A, B and D. The results of paper A and B show that the use of a value model to capture high-level needs allows for a wider definition of the design space and can enable the inclusion of potential new design dimensions. Paper C illustrates how the translation of the existing requirements into functions and constraints can open up new design dimensions and allow for a wider search space which is defined in a more systematic way.

It has also been observed in all studies that the product's functions are not captured in a systematic method or tool. Similarly, the use of design rationale capture or other abstract product models could not be observed. . The lack of these product models reduces the possible insight into potential impacts of product changes, sub-system introductions and replacements. Paper C and D build on these observations that the impact of (new) product functions and constraints on the product structure are commonly not captured, and a function modelling approach is proposed and implanted as an architecture model to define the design space as well as provide an initial exploration of alternative solutions. The function model in EF-M captures the original design, and with it, the respective design space boundaries in the form of requirements and constraints.. The

use of the architecture model enables an overview of the impact of such a constraint change, or for any change on the design in general.

**Population with novel concepts**

The population of the design space with concepts covering all design space dimensions proved to be the largest challenge in the DSE projects. Design space population in product development, especially in the concept development- and selection phases, builds heavily on the use of product models for representation and analysis of the concepts. Creating a CAD model of a product is a time and cost intensive exercise, and accordingly it is also expensive to edit a CAD model. This effort increases with the complexity of the product, as has been observed as a challenge in Paper B and furthermore been recognised in Paper D. Hence, if alternative configurations or designs are to be explored, a costly change of the existing model is required. The rigidity of CAD models has furthermore not only be recognised in the results of the appended papers, but in literature, i.e. by Heikkinen et al. (2018) or Aish and Woodbury (2005). While in certain KBE approaches parameterised CAD models have been used, they mainly only allow changes in dimensions or modules.

Therefore, in paper D a DSE methodology using a function model as method for design space population is suggested. The suggested method, illustrated in Figure 4.7, is built on the cumulated experiences from papers A, B and C. New concepts can be invented with different levels of product abstraction and levels of maturity, and be integrated into an existing product structure. The function model allows for a higher coverage of design space due to its lower level of fidelity.

For novel solutions, the use of function models in the form of EF-M has shown to be efficient in populating the design space. The description of the design space in constraints and functions provided the guidelines needed for developers to find a host of novel solutions, reported in papers C and D and seen in the project attached to paper A. All novel solutions were captured in EF-M models, and through the combinatory tools of EF-M and CCM different instantiations could be created which combined different sub-solutions into concepts. However, the challenges arose when embodying the concepts into geometry models, throughout all projects. To be able to assess a design in respect to constraints, feasibility and value, a geometry model was required in all cases. To convert the concepts from a function-model to a geometry model, a new or partially new CAD model needed to be generated by human intervention. To be able to explore a wide design space, many designs need to be assessed. However, this would require an automated or semi-automated process (La Rocca and van Tooren, 2007).

**Analysis of concepts**

As explored in Paper B and D, another limitation beyond the population of the design space is the lack of knowledge about new solutions and their impact on the system level. Since novel solutions are exactly that, novel, they are not modelled, analysed or otherwise explored yet. Therefore, tit is difficult to predict their behaviour, especially not in interaction with the original product system. To get this knowledge about the behaviour of the novel solution and product, it would be necessary to create a model and analyse it. Paper B projects a through-life data collection system

which would be enable developers to gain insight about individual design decisions' impact on the entire product life cycle, by reusing the knowledge from earlier designs.

However, the design space exploration methods implemented in papers A, C and D allows for the analysis of systemic product properties captured in the function model. The information captured in the hierarchical structure as well as the modelled interconnections of the EF-M model allow for early-phase analysis such as modularisation or product complexity. Levandowski, Müller and Isaksson (2016) report about an application of this.

The lack of knowledge about novel solutions also brings the challenge to compare them to existing ones. Most likely the solutions will have a different TRL, and therefore in comparison of robustness, reliability and implementation the traditional approach is always beneficial. Especially in industries where safety and reliability are of high concern, such as the aerospace industry, this is often a hinder to the introduction of new solutions that have not undergone a long and tedious verification process. Paper A illustrates this problem, and the papers C and D provide conceptual DSE approaches under consideration of varying TRL between different sub-solutions.

To be executed on a large number of alternative designs, the analysis of them requires a certain degree of automation. Successful DSE covers a large section of the design space, hence a large amount of different designs needs to be analysed. Since the numbers of alternatives can be several hundred or more vastly different designs, a manual analysis would be very resource intensive. However, many observed industrial applications as well as academic research already employ automated MDA systems that create consistent results from multiple analysis on multiple designs, hence there are already potential solutions to this challenge available.

**Towards a faster, wider and more systematic design space exploration**

In all appended papers, the use of models with a higher level of abstraction than CAD, such as value models in the form of EVOKE or function models in the form of EF-M, has shown an improvement to the description, population and analysis of the design space. This has been achieved by opening up new design dimensions in the description, through capturing of product functions and design space constraints, together with their relationship between the individual solutions. The population of this systematically defined design space showed to be easier when handling higher-abstraction models in the function modelling domain instead of geometry models. The introduction of novel solutions or sub-systems could be achieved without the challenges observed with altering CAD models. Furthermore, the ability of EF-M to combine sub-solutions in a factorial fashion into concepts automated the coverage of a wider area of the design space. Furthermore, it enabled the analysis of systemic properties and to check individual concept properties against the constraints for model feasibility.

However, the embodiment of these concepts from the function into the geometric domain proved to be a major challenge. An automated process in this stage is necessary to cope with the larger amount of designs. However, while the presented methods rely on this embodiment process, no proven solution has been identified yet.

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# 5 Discussion

*Bringing the results of the appended publications into the context of the research questions and academic literature*

The four appended papers, which have been described in the chapter above, together contribute to the answering of the two overarching research questions. These are:

**RQ1***: What are factors limiting product developers in exploring the design space in the concept development?*

**RQ2***: How can design space exploration be improved to be faster, more systematic, and cover a wider area of the design space?*

Since the publications and studies had different goals, targets and audiences, they do not chronologically contribute to the two questions. The following Table 3 illustrates in which paper contributions to which research question can be found:

Table 3 Research questions addressed in appended papers. Circle size approximately correspondents to amount of contribution.

|  | Paper A | Paper B | Paper C | Paper D |
|---|---|---|---|---|
| **RQ1** | ● |  | ● | ● |
| **RQ2** | ● | ● | ● | ● |

As described in Chapter 3.1, the questions can be sorted into one descriptive question, RQ1, which inquires into the current state of practice, and one prescriptive question, RQ2, which investigates possible solutions on how to improve said state.

The results in relation to the research questions are discussed in below.

To enable product developers to better define the boundaries of the design space as well as populate it with different concepts that span a wide variance and variation a combined function-geometry modelling approach for DSE is suggested. While there are several geometry model based design space exploration methods available, e.g. eifForm by (Shea, Aish and Gourtovaia, 2005) or DEE by (La Rocca and van Tooren, 2007), they all rely on heavily specialised CAD models. Therefore, they only allow for the exploration of alternative geometry variants with different modular composition or alternative dimensioning – the search spaces are limited to modules or dimensions. To be able to use an extended search space, other modelling approaches such as function models are required – as has been illustrated in paper B. However, these modelling approaches capture the product concepts on a different level of abstraction. Figure 5.1 illustrates different levels of abstraction for different product modelling approaches, similar to as seen with Hirz et al (2013), but extended to include value models. Different product models which are mentioned in this thesis are illustrated with a circle. When applied in a product development method, these models can be used to bridge different levels of abstraction. A parametric CAD model, when instantiated in a static CAD model, has a reduced level of abstraction. Similarly starts an EF-M model with abstract functional descriptions and ends with more concrete technical solutions. These abstraction-bridges are illustrated in Figure 5.1 in bars behind the modelling languages.



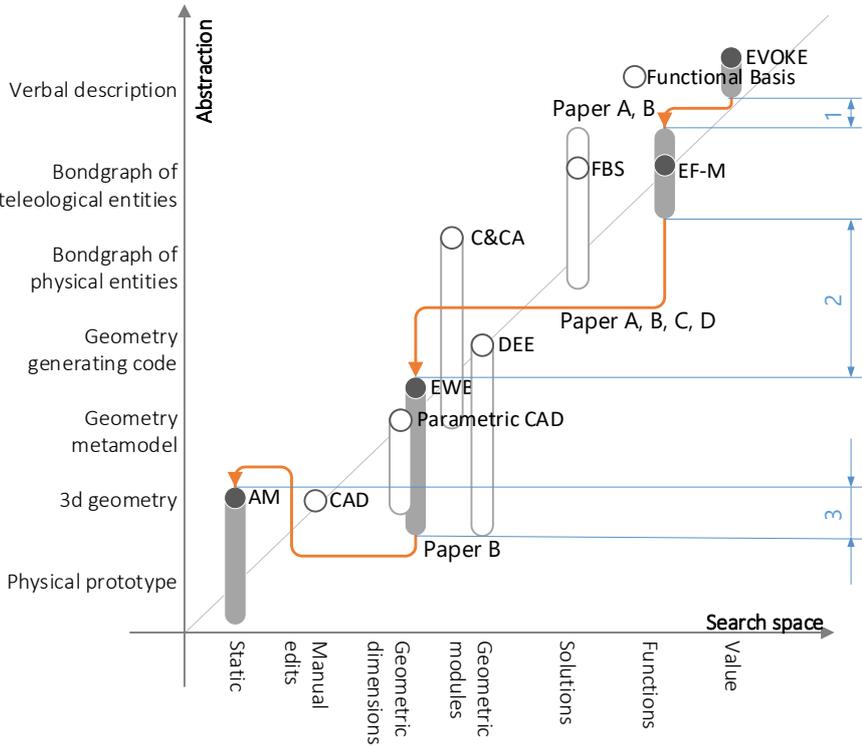Figure 5.1 Model abstraction vs available search space of selected product development methods and models. The methods which have not been applied in the appended papers are: Function-Behaviour-Structure modelling (FBS) (Gero and Kannengiesser, 2004), Contact and Channel Approach (CCA) (Albers *et al.*, 2011), and Design and Engineering Engine (DEE) (La Rocca and van Tooren, 2007), as explained in the frame of reference above.

On the x-axis, Figure 5.1 shows a range of search spaces which increase from a static, unsearchable model to being able to explore different value dimensions. The alignment of product models to search spaces is based on the experience in their application and literature research.

The methods and models that have been used in studies and publications contributing to this thesis are presented in dark grey, while other methods and models which are only mentioned are illustrated in their outlines. In Figure 5.1 the chosen approaches of the individual papers are illustrated with the orange line, showing the coupling of different modelling methods from EVOKE, through EF-M and EWB up to Additive Manufacturing (AM), which was only applied in paper B.

Each of the applied methods matures the information content of the respective models through the different levels of abstraction. However, as can be seen in Figure 5.1 in blue dimensioning lines, there are significant gaps in abstraction between the different methods and their respective models. The wider the gap, the mode work needs to be invested to connect the methods. This has been seen again and again in each project, and is documented in papers A through D. However, between EWB an AM the methods actually overlap, gap (3), which makes for a very easy connection. The information in the geometry model of EWB can without much effort be transferred to the AM machinery. The smaller gap (1) required minor data modification and format adaption, while the large gap (2) involved the creation of novel models and datasets which required manual connection to the EF-M dataset. This creates a bottleneck of information flow which reduces the amount of explored design alternatives. This has been identified as the main challenge for a faster, wider and more systematic design space exploration.
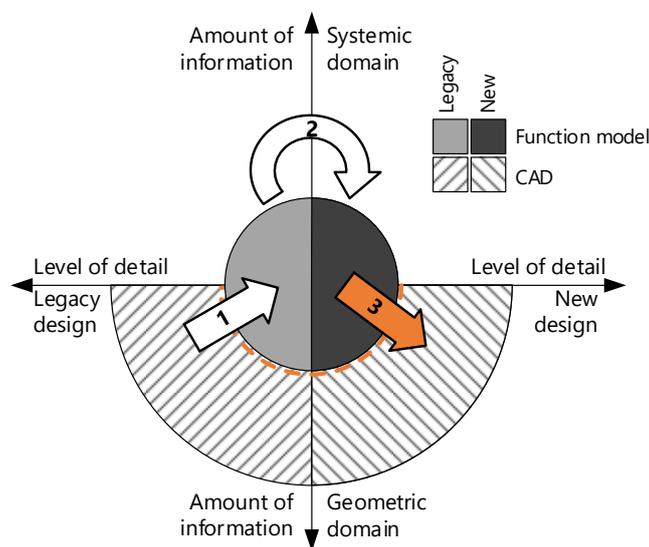


Figure 5.2 Gap in model connectivity explained in DSE approach model from paper D, with the process of embodiment (3) highlighted.

From this it can be derived that a chain of product development methods is more efficient the higher the vertical overlap of the methods. If a method chain shows gaps in the abstraction levels, these need to be filled by human interaction and work. The "perfect Design Space Exploration method" would be support modelling maturity throughout all abstraction levels while enabling a search space on each level. This has been attempted in papers A and B, where in both cases a value model provided a wide search space, and the subsequent modelling methods aimed at maturing the product towards a more concrete model. However, the above mentioned gaps remained and provided a challenge.

While the design space exploration method presented in paper D and illustrated in Figure 4.7 claims to "connect the functional and geometric modelling domains" (Müller, Isaksson, *et al.*, 2018). However, when looking at the gap (2) in Figure 5.1, the connection is not actually given. This is also stated under "further work" in said publication, and throughout papers A to D. The actual connection between the different levels of abstraction cannot be facilitated yet in an automated fashion. Figure 5.2 reproduces the DSE method from Figure 4.7, but highlights the challenge to connect between the two modelling domains in process (3) embodiment.

While the challenges for DSE, in response to RQ1, are listed above as lack of methodology to define the design space, rigidity of geometry models hindering the generation of novel and radical product models which would be needed for analysis of their behaviour and the challenge to capture and compare product concepts of different TRL, they can be reduced to the following two points:

For design space exploration to be faster, wider and more systematic, it requires product development methods and models which enable a wide search spaces on each level, i.e. from value to geometry level, and a gapless methodology throughout all abstraction levels. Which in turn answers RQ2.

To enable DSE in this fashion, the approach illustrated with the orange line in Figure 5.1 needs to be improved mainly through the closing of gap (2). This can be done by either expanding the used function modelling approach to reach a lower level of abstraction, or to have the geometry modelling approach EWB to already connect to higher abstraction levels. A third option is the introduction of a new modelling method which closes the gap, such as CCA or DEE, which can be seen in Figure 5.1 to overlap both EF-M and EWB.

The Contact and Channel Approach (CCA) provides a geometry description beyond pure geometry, but describes how a geometry fulfils its function. Therefore contact surface pairs are identified which are seen as the main, which channel each and every exchange of energy, matter and information (Albers and Matthiesen, 2002). The modelling approach has been shown to support failure analysis by supporting the understanding of the product's function (Gladysz and Albers, 2018). Since it provides a connection between function- and geometry representations, as can be seen by the coverage in Figure 5.1, it could be the missing link for the above mentioned DSE approach. However, the actual connection to both function and geometry mode would require further work.

The Design and Engineering Engine (DEE) is a KBE method which aims to enable engineers in creating a large variety of CAD models to explore alternative combinations. To do this, High Level Primitives (HLP) are re-combined to explore a modular-geometric search space, and the created geometry models subsequently undergo multi-disciplinary analysis (La Rocca and van Tooren, 2007). As opposed to CCA, DEE is described as a DSE method, exploring and analysing different configurations. However, La Rocca and van Tooren (2007) state that the aim is to automate the non-creative parts of the work process, i.e. no decisions upon which design is best are made. Furthermore, the method has no connection to the concept of product function or value, which would need to be established. On the other hand, since the method is capable to bridge abstraction to the 3D geometry level, it could substitute EWB as a geometry creation tool.

# 6 Conclusions

*A summary of what the presented research has led to, and may lead to in the future.*

The research presented here is aimed at both understanding as well as improving design space exploration. Therefore, both the results of an analysis of the current state in industry as well as suggestions for novel methods are presented.

 "Design Space Exploration" in its widest definition is always an activity in the process of product development, since the three steps *define – populate – analyse* are always performed to a degree. However, to be able to develop better products, more alternative designs need to be generated and analysed, i.e. a wider area of the design space needs to be explored.

A major observed limitation in industrial practice lays in the way the design space boundaries are described and defined. There has been no observed methodology that systematically captures constraints and functions of a product, and through this describes the design space's dimensions and boundaries. This reduces the number of explored alternative solutions to only a subset.

The limitations in the generation of alternative designs covering the entire design space is the rigidity of the product models used to represent the designs, which are commonly geometry models in CAD. The variation of these models to integrate novel solutions is time consuming and requires expert knowledge in the modelling method. Furthermore, most product development process build on a legacy model, which already prescribes the starting point for DSE. As a result of this, the search space is limited to geometrical variations in the proximity of the legacy design.

As a way of improvement of DSE, the use of function- and architectural models, specifically Enhanced Function-Means modelling, is suggested. Such models allow for the capturing of design space limitations in the form of constraints and functional requirements, and enable the evaluation of solutions towards these design space boundaries already in an early phase. This systematic definition of the design space exploration enables the coverage of a wider design space, and furthermore introduces a more robust process.

The use of function models can also be a remedy against the rigidity of existing product models. They are able to capture both the existing design, the design space boundaries as well as novel

solutions on different levels of the model hierarchy. To implement this approach, it necessary re-introduce these novel concepts which have been captured in the architecture model into the geometric domain. The main challenge in this work is bridging the gap between the different abstraction levels in the function modelling and geometry modelling domain needs to be closed.

A gap in the abstraction levels of product development methods is discussed as being the source of these challenges. While the applied methods do cover search spaces of different levels, the development process is held back by a gap in the abstraction levels between function- and geometry models.

## 6.1 Future Work

To be able to develop a fast, wide and systematic design space exploration of complex engineering products according to the approach described in Chapter 4.5, a connection between the function and geometry modelling domain needs to be established. As is illustrated in Figure 5.1, to ensure a coherent design process throughout all levels of abstraction, the EF-M and parametric CAD modelling environment need to be connected. The respective gap is illustrated as (2) in Figure 5.1. A product modelling method covering this gap needs to be able to receive the information from the function model in EF-M and mature it to the level where it can be used as an input to the parameterised CAD environment. By doing so, it also needs to enable the exploration of the search spaces of alternative product solutions and geometric modules. A potential approach for this is the inclusion of Contact and Channel Approach (C&CA) (Albers and Sadowski, 2014). As is illustrated in the figure, C&CA covers exactly abstraction scale between the already applied methods. However, C&CA only acts on a limited search space, hence it might be necessary to develop an entirely new modelling approach. The modification or re-use of elements of other automated geometric design space exploration methods, such as DEE (La Rocca and van Tooren, 2006) or grammar based Computational Design Synthesis (CDS) (Königseder and Shea, 2015) may also be promising options.

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*The knowledge that has been reused to procure this research*

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