THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Applying lean principles and set-based approaches in product development

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A simple test rig for generating a haptic feeling, controlled by a hobby computer.

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Abstract

The research described in this thesis addresses the problem of transformation to lean product development (LPD) and how to introduce and support the use of set-based design (SBD) in the concept development process. The original description of SBD does not define how to generate, evaluate and reduce a set of design solutions. Evaluation of solution candidates, which are too complex to be analytically verified, or are driven by qualitative criteria, has here been given special attention, particularly in cases when methods utilising human judgment may be needed. For some products, the solution space can consist of both principally different *alternatives* and parameterised *variants* of these. The question here is if established methods can be combined and introduced in an efficient way to support an SBD process for development of such products, when driven by both quantitative and qualitative criteria.

The research approaches used are:

- a two-case study (Yin, 2009),
- the design research methodology (Blessing and Chakrabarti, 2009) and
- the scientific work paradigm (Jørgensen, 1992),

the last two combined with multiple case studies. Also, elements of action research (Oosthuizen, 2002) are used.

The results show that the principles and introduction of LPD were experienced as positive by participating practitioners in the conducted case studies. It was furthermore shown that SBD can be introduced and applied in a workshop at team level within a time frame of one or two working days if the design problem at hand is not too complex. Another result is that SBD can be combined with and supported by established methods such as creative and systematic methods for synthesis, enhanced function-means modelling, axiomatic design, extended causal diagrammes, interactive evolutionary algorithms (IEA) and Pugh matrices for generation, analysis, evaluation and reduction of a solution space of design alternatives and variants of these. Both qualitative and quantitative requirements can be handled.

The conclusions are that a transformation to LPD is facilitated by information about good examples and internal support by management. Also, the existence of a lean enthusiast in the organization and an appropriate implementation plan supports a transformation to LPD. A function to maintain the LPD system as well as influence of the lean principles are valuable guides on how to use LPD.

Also concluded is that a seamless, efficient process, applying set-based principles, for synthesis, evaluation, and reduction of a solution space of *design alternatives* can be created by combining enhanced function-means modelling, morphological matrices, axiomatic design, causal diagrammes and Pugh matrices. Such a compound of methods can be introduced and applied in a workshop at team level within a time frame of one to two days when solving well-known and not too complex design problems. The workshop should be facilitated by an expert on the methods used and initiated and surveyed by a team manager. Furthermore, a solution space of parameterised *design variants*, with criteria that are either qualitative or too complicated to be numerically defined, can be generated, evaluated and reduced in such a process. By using a defined set of functional and constraining criteria, and applying axiomatic design and IEA, a *variant* solution space can be generated and refined. A set-up of the IEA that does not overburden the user should be preferred.

Keywords: Concept development, Lean product development, Set-based design, Controlled convergence, Lean transformation, Industrial introduction

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Mikael Ström

Appended publications

This thesis is based on the work presented in the following papers:

Paper A Ström, M., Alemyr, M., Bükk, S., Gustafsson, G., and Johannesson, H. (2012) "Transformation to lean product development - Approaches at two automotive suppliers". Proceedings of International Design Conference, DESIGN 2012.

Paper B Ström, M., Raudberget, D., and Gustafsson, G. (2016) "Development of a methodology to implement set-based design in a day". Proceedings of International Design Conference, DESIGN 2016.

Paper C Ström, M., Raudberget, D., and Gustafsson, G. (2016) "Instant Set-based Design, an Easy Path to Set-based Design". Procedia CIRP Design Conference 2016.

Paper D Gustafsson, G., Raudberget, D., and Ström, M. (2016) "Unveiling Fundamental Relationships in Industrial Product Development". Procedia CIRP Design Conference 2016.

Paper E Ström, M., Gustafsson, G., and Johannesson, H. (2022) "Efficient Set-Based-inspired generation and elimination of alternative design concepts". Submitted to the International Journal of Product Development.

Paper F Ström, M., Wolff, K., Jean-Jean, J., Gustafsson, G., Isaksson, O., and Johannesson, H. (2022) "A set-based-inspired design process supported by axiomatic design and interactive evolutionary algorithms", Accepted for publication in the International Journal of Product Development.

Work distribution

The work distribution between the authors of each appended paper is as follows:

Paper A — The idea to do the research was proposed and formulated by Mikael Ström together with Hans Johannesson and Göran Gustafsson. The work was organised by Mikael Ström who also did the research design. Data was collected by Mikael Ström, Göran Gustafsson, Mats Alemyr and Stefan Bükk. Core findings were identified and described by Mikael Ström, Göran Gustafsson and Mats Alemyr. Mikael Ström did the main writing with support from Göran Gustafsson and Mats Alemyr. Stefan Bükk contributed with knowledge in lean product development. Valuable comments were made by Hans Johannesson.

Paper B — The idea behind the paper was proposed and formulated by Mikael Ström, who also did the research design and organised the research work. The combination of methods and their application was designed by Mikael Ström. Data was collected by Mikael Ström, Göran Gustafsson and Dag Raudberget. Mikael Ström and Dag Raudberget wrote the main part of the paper with support from Göran Gustafsson.

Paper C — The idea behind the paper was proposed and formulated by Mikael Ström, who also did the research design and organised the research work. The improved combination of methods, compared to paper B, and their application was designed by Mikael Ström. Data was collected by Mikael Ström, Göran Gustafsson and Dag Raudberget. Mikael Ström and Dag Raudberget wrote the main part of the paper with support from Göran Gustafsson.

Paper D — The idea behind the paper was proposed and formulated by Mikael Ström and Göran Gustafsson. Mikael Ström did the research design and organised the research work. Theoretical analysis of industrial cases was done by Göran Gustafsson. Göran Gustafsson wrote the main part of the paper with support from Mikael Ström and Dag Raudberget. Mikael Ström and Dag Raudberget wrote the section about the research process and the discussion. All authors contributed to produce the core findings.

Paper E — The idea behind the paper was proposed and formulated by Mikael Ström and Hans Johannesson. Mikael Ström conducted the research design and organised the research work. Data was collected by Mikael Ström and Göran Gustafsson. Mikael Ström wrote the paper with assistance from Hans Johannesson and Göran Gustafsson. Hans Johannesson conducted complexity and dependency analysis in the CCM software. Göran Gustafsson wrote essential parts of the paper concerning causal diagrammes. Core findings were identified and described by all authors.

Paper F — The idea behind the paper was proposed and formulated by Mikael Ström and Hans Johannesson. Mikael Ström did the research design and organised the research work. Data was collected by Mikael Ström, Jeremy Jean-Jean and Krister Wolff. Krister Wolff supported with basic knowledge in the field of interactive evolutionary algorithms. Software applications were developed and described by Mikael Ström and Jeremy Jean-Jean with support from Krister Wolff. Core findings were identified and described by Mikael Ström, Göran Gustafsson and Hans Johannesson. Mikael Ström wrote the main part of the paper with assistance

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List of abbreviations and acronyms

AD	Axiomatic Design
C	Constraints
cap	Customer Application Properties
CCM	Configurable Component Modeler
DP	Design Parameter
DRM	Design Research Method
DS	Design Solution
DS X	Descriptive (DRM) Study number X (can be I, II, III …)
ED	Engineering Design
EM	Electro-mechanical and Mechanical
EF-M	Enhanced Function-Means
F-M	Function-Means
I	Current
IE	Integrating Event
IEA	Interactive Evolutionary Algorithm
ip	Inside Property
ISBD	Instant Set-Based Design
KO	Knowledge Owner
KVS	Knowledge Value Stream
LPD	Lean Product Development
MM	Morphological Matrix
NASA	National Aeronautics and Space Administration
P	Power
PBD	Point-Based Design
PD	Product Development

PS	Prescriptive Study (DRM)
PVS	Product Value Stream
R	Resistance
RC	Research Clarification
RQ	Research Question
SBD	Set-Based Design
spp	Selling Point Properties
SPS	Structured Problem Solving
SWP	Scientific Work Paradigm
U	Voltage
VP	Visual Planning

1 Introduction

1.1 Background and research questions

The focus in industrial product development is to launch products of desired quality on the market in short lead times, to be competitive and secure an economical return from the investment in development work. However, the quality of products, in some cases, appears to be poor (Suh, 1990). One sign of this is the many recalls of delivered cars in the automotive industry (Ni, 2017). As product development in general is subject to trade-offs of different kinds, the difficulty of handling these between quality, cost, and lead time might contribute to the perceived quality losses. High-quality products can be developed and produced, but often to a high cost and/or required lead-time. Cost and development time can also increase due to iterations. A new design alternative then needs to be explored, and the design process loops back.

Many of today’s products are built up by several different components. These often involve different technologies and are made by different producers. They can also appear as scaled members of a parameterised product family. Examples of this are cars, aeroplanes, computers, medical equipment, white goods etc. These products are complex, and the processes to develop them often becomes both multidisciplinary and multidimensional, involving different knowledge domains as well as synthesis and analysis on both the basic concept and the parametric level. This calls for cooperation between individuals with knowledge in these domains. There is a need to manage complexity and internal dependencies in these products. There is however no single support method for this, and the knowledge in industry about existing methods, from design research, is poor (Gericke et al., 2020).

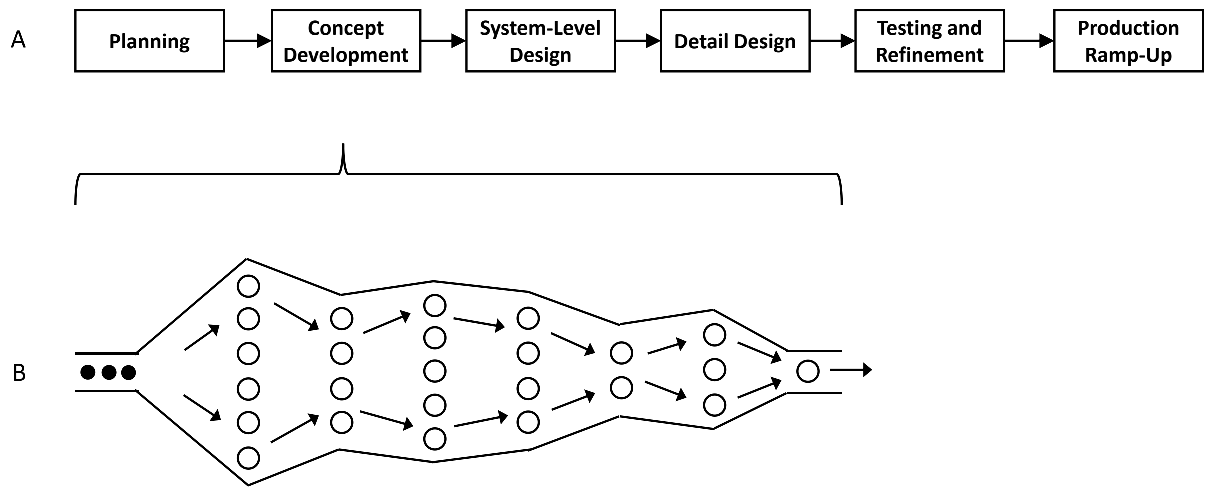


Figure 1. Phases in product realization (after Ulrich and Eppinger, 2012). View A is the product realisation process and view B is the concept generation and elimination phase.

One attempt to manage this situation is to divide the product development process into phases (see Figure 1). Examples of this are found in Andreasen and Hein (1987), Blanchard et al. (2014), Pahl (2007), Pugh (1996) and Ulrich and Eppinger (2012). The phase approach was formalized by Cooper (1994) in the Stage-Gate® model. A similar concept is the Phase-Review model created by NASA (Wikipedia 1, 2021). The concept of phase-review is here referred to as phase-based process models. The phase approaches do not alone provide the means to master product development work in a sufficient way in industry. On the contrary, there are some drawbacks of, and problems associated with, the phased processes. These have in recent years become topics of discussion. The phase-based time plan imposes an end date on the project, and it might be tempting to pass by reviews without fulfilling stated requirements to comply with the plan. This is a devious behaviour in which time keeping takes priority over necessary development work in the PD process, since not dealing with issues when they appear likely causes delays later, when the problems become acute. Two examples are wishful thinking when filling-in review documents and too much focus on formal procedures. The management may tend to regard the review documents as sufficient evidence that the project is running well, instead of digging deeper into what is really going on and assuring that the knowledge gaps are closed before the development work proceeds.

Another, more fruitful, approach is to focus on the needed knowledge to assure quality of the product. One manifestation of this is to test many potential solutions early in the process to learn, instead of a few late to verify something that you think that you already know (Ward, 2009). Knowledge is then gained earlier, when the degree of freedom is higher, which enables fact-based decisions and feasible solutions. There are examples of firms that manage to develop products on time with a high quality. One well-known example is Toyota Motor Corporation. Toyota has been studied by western researchers, and based on their findings, Lean Product Development (LPD) methods have been identified. These methods, used at Toyota, are described by scholars such as Morgan and Liker (2006), Sobek et al. (1999), Ward (2009) and Ward et al. (1995), and their findings have been used by others with good results. Examples of this are Kennedy (2008), Majerus (2016) and Oosterwal (2010), who describe different implementations of LPD.

The framework of LPD provides principles that serve as guidelines of how to perform product development work. One set of principles is supplied by Morgan and Liker (2006) and another one by Ward (2009). These principles have slightly different foci but are still compatible to a large extent. They have been tested in many cases, as mentioned above, and proven relevant to improve product development work. Each set includes one principle which advocates the use of Set-Based Design (SBD), that is described by its own principles.

SBD employs a set of solutions which makes up the solution space. As more knowledge is gained about the solutions during the development process, less feasible ones are eliminated, and the superior solution remains. A prerequisite for applying the SBD approach is the support for synthesis and analysis of solution alternatives. In industrial case studies (Ström et al., 2016B) it has become apparent that firms often lack knowledge about existing methods for generation, combination and elimination of solution alternatives.

The set of LPD principles, defined by Morgan and Liker (2006), concerns a socio-technical system of which SBD is one component (see Figure 2). In a similar fashion, Ward (2009) mentions the lean development systems which SBD is part of. This motivates a study of the introduction of LPD as well as the introduction of SBD in product development. To take full advantage of LPD it is of special interest to explore the need for methods supporting synthesis and analysis in the SBD process (see Figure 2).

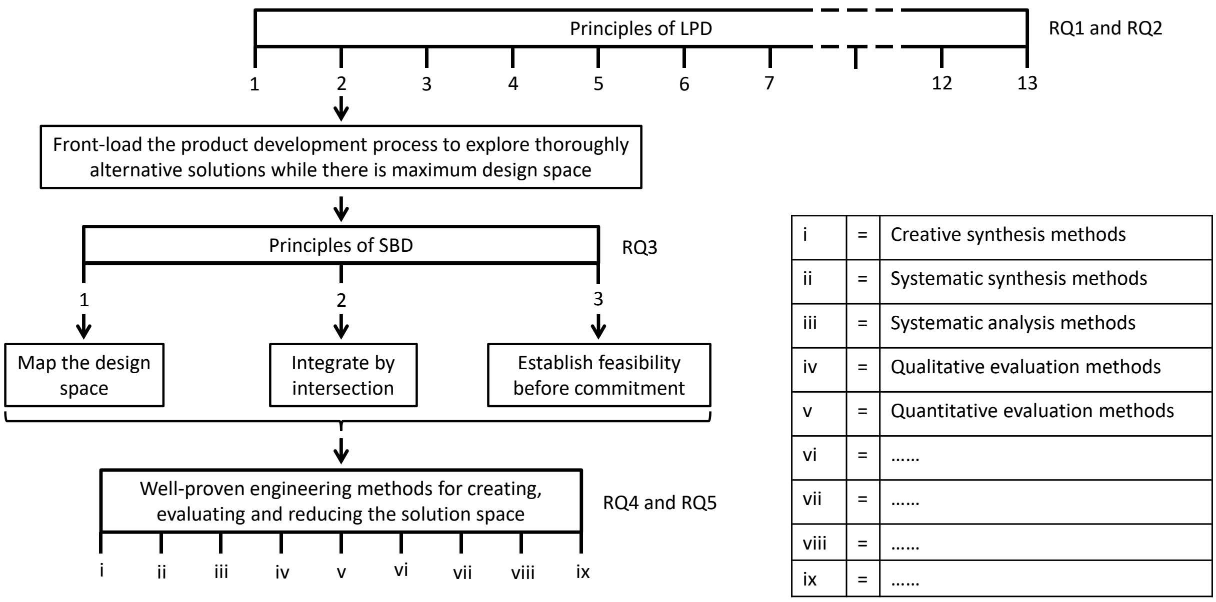


Figure 2. The suggested combination of LPD principles and engineering methods with related research questions. The 13 principles of LPD are according to Morgan and Liker (2006), and the three principles of SBD are according to Sobek et al. (1999). See also Figure 11.

In the automotive sector, a large portion of a car is produced by tier 1 (component and subsystem) suppliers, who often handle very strict demands from the car manufacturer regarding price, quality, and delivery time (Nieman et al., 2018). Some suppliers manufacture components according to a fixed specification (often called build-to-print) while others develop products of their own. Many of them use phase-review processes and suffer from the drawbacks described above. One way to mitigate these could be to introduce LPD. There is however a lack of contrasting scientific studies of and experiences from LPD introduction at different kinds of suppliers.

The focus of this research is the introduction and application of LPD, with its principles, emphasising the use of SBD in the concept development process. In this context we find it relevant to pose the following research questions:

RQ1: What experiences are there from introducing LPD at tier 1 suppliers?

RQ2: How should an introduction of LPD be improved at tier 1 suppliers?

Even though SBD is a promising way of developing products, the method is still not widely used (Flores et al., 2017; Godbole et al., 2019). SBD is challenging to introduce for several reasons. It is usually considered difficult to combine with traditional phase-review project models (Morgan and Liker, 2006; Kennedy et al., 2008), which are common ways to organize an industrial development process. Another challenge, not described in the literature, is how to, in a quick way, generate a set of solutions and to find good reasons to eliminate inferior members. Even though this is central in SBD, there is no coherent set of methods for it. Furthermore, there is little guidance available on how to quickly introduce and apply SBD in an industrial firm. From this, the following research question is proposed:

RQ3: How should a Set-Based-inspired design process be efficiently introduced in a development team within a reasonable time frame?

Methods to support generation, evaluation and then reduction of a solution space are lacking in SBD. However, different methods that address these issues are provided in the product development literature. Different authors describe and advocate an extensive body of such methods (Andreasen and Hein, 1987; Blanchard et al., 2014; Pahl, 2007; Pugh, 1996; Ulrich and Eppinger, 2012), of which many have also been applied in practice with good results. There is however no single method that can handle all tasks in the concept development process. For example, specification, synthesis, analysis, and decision making, require different techniques. Gericke et al. (2020) argue that instead of continuing to develop new methods, it is worth combining already existing ones in a meaningful way.

SBD is assumed to be a suitable framework (Al-Ashaab et al., 2013) for a process with such a combination of methods. The process should be able to generate a set of design alternatives of the two-dimensional solution space (see Figure 3). Creative and systematic synthesis methods (Ulrich and Eppinger, 2012; Pahl, 2007) might be used to generate the solution space. A logical next step would be to analyse and decompose the generated solutions. EF-M (Enhanced Function-Means) models have a proven potential (Müller et al., 2019) to describe, decompose and explore members of the solution space of design alternatives. The set of solution alternatives then needs to be further analysed and evaluated, and trade-offs between different alternatives may become necessary.

Axiomatic design (Suh, 1990) is an interesting theory for handling these kinds of design problems. Two axioms are the foundation of this theory. The first is the dependency axiom, that helps eliminate products with functional couplings, and the second the information axiom, that rules out too complex solutions. The concepts of functional coupling and complexity are often not fully grasped by practicians in industrial firms. Such issues will not always be obvious, and tools to reveal them in different design concepts are needed. Then, when functional dependencies need to be judged, the design can be further analysed regarding causality of entities. This might reveal how severe a functional dependency is. There are several tools by which this information can be utilized to compare and rank design alternatives. One example is the Pugh matrix (Pugh, 1996). In this context we pose the following research question:

RQ4: How should a set of existing methods and tools be combined to facilitate an efficient process for synthesis, evaluation, and reduction of a solution space of design alternatives?

In parameterised Electro-mechanical and Mechanical (EM) products, new variants are often created by varying governing parameters. When this possibility to increase the number of solutions is exhausted, the next step is to consider new and principally different design alternatives. Another reason to do this can be the appearance of a new technology, like, e.g., the electric driveline in the automotive industry and microprocessors in telephones. Autonomous vehicles and lawn movers, and stoves with ceramic tops are other examples of recent design innovations. The solution space of these types of products has two dimensions (Ward et al., 1995). The first is principally different alternative designs, and the second dimension is parameterized variants of these (see Figure 3).

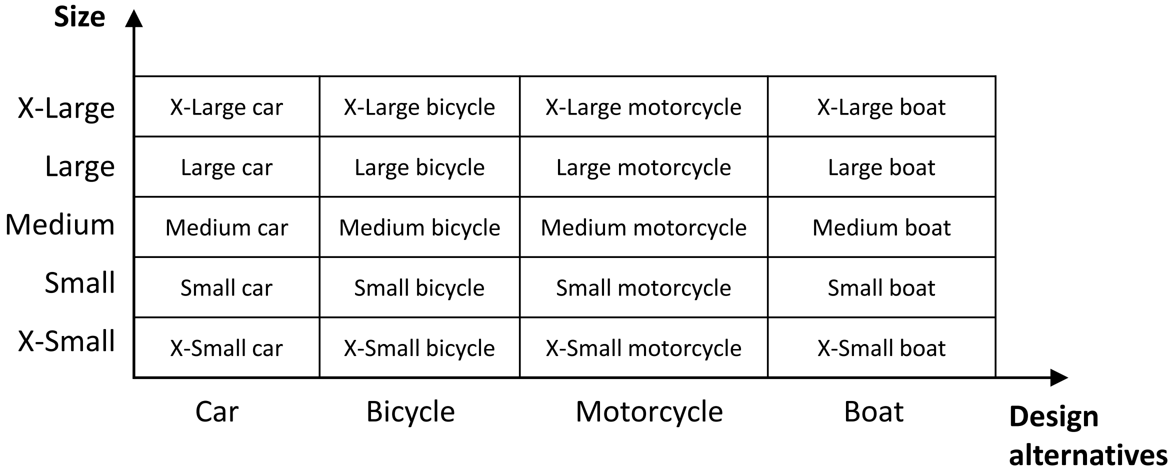


Figure 3. A two-dimensional solution space of means for personal transport.

In the original descriptions of SBD, little is said regarding which methods to use for generation, evaluation, and reduction of the solution space in relation to product specification contents and criteria characteristics in its second dimension (Ward et al., 1995). Constraints limit how much parameterized solutions can be varied. When the design space is defined by quantitative criteria, it can often be explored using computational methods (Papalambros, 2000). This is not the case when criteria are of a qualitative nature. When evaluation of the design in numerical terms for some reason cannot be carried out, it is not possible to use computational methods. In such cases, human judgement is needed. Examples are when a product should be aesthetically appealing (Brintrup et al., 2008) or convey a particular haptic feeling (presented in the appended paper F). A third example is when the producibility of a part is assessed (Lucik et al., 2017). Interactive Evolutionary Algorithms (IEAs) (Dawkins, 1996) is a suitable tool in these cases. In this context we pose the following research question:

RQ5: How should solution spaces of design variants be generated and evaluated in a Set-Based inspired process when they are limited by criteria which are qualitative or too complicated to be numerically defined?

The scope of this thesis is need-based development of EM products in an LPD context. Of interest is efficient introduction and application of useful methods for synthesis and analysis to complete the SBD approach. This includes well-proven support methods for specification of criteria, synthesis of a solution space, analysis and evaluation of solution candidates, and elimination of inferior ones – all in a set-based-inspired seamless process – where feasible solutions, which are not necessarily optimal, are sought. In this way the SBD shortcomings regarding synthesis and analysis are overcome.

1.2 Delimitations

Organisational aspects on product development, as well as product architecture and platform approaches are not considered in this thesis. Nor are development issues related to customer needs analysis, product service-systems, eco-design and production processes.

1.3 Outline of this thesis

The thesis is divided into seven chapters which are described in Table 1 below.

Table 1. Thesis outline.

No.	Chapter	Contents
1	Introduction	Presentation of the background that motivates this work and the posed research questions, and the delimitations of the thesis.
2	Frame of reference	Description of the theories and methods that are related to this work.
3	Research approach	Presentation of the used approach, regarding scientific methods and way of working.
4	Performed studies and results	Summary of the appended articles, with performed studies and results.
5	Discussion	Discussion of the results regarding reliability, generalizability, scalability, and validity.
6	Conclusions	Conclusions based on the results and the discussion.
7	Future work	Topics for future work are suggested.

2 Frame of reference

Theories and methods referred to and used in this work originate from different areas in design science: Engineering Design (including creative and systematic methods), Lean Product Development, and Axiomatic Design. In addition, Interactive Evolutionary Algorithms has been identified as a useful tool to support design of parameterized products.

2.1 Engineering design

Engineering design, as described by Pahl et al. (2007), is a comprehensive set of methods and tools to cope with different steps in the design of products. The process is depicted as a flow chart with significant phases in the design process. There are well established methods and tools for different tasks in the workflow. A similar approach is provided by Ulrich and Eppinger (2012). Many of the methods are in common and judged as very useful in engineering design. Pugh (1996) has a more holistic perspective described in an activity model where both the business aspects and the design aspects of PD are included. Concept generation is in all these approaches a significant part of engineering design. It is followed by different methods to identify the concepts that will be further refined and designed in detail in the later phases of the PD process.

2.1.1 Product criteria

Product design problems are specified by using different types of criteria describing the pre-requisites of the design task. In design theory there are different descriptions of these criteria. Those that are based on customer needs are established early in product design (Ulrich and Eppinger, 2012), first at the system level and then decomposed to more detailed levels. Criteria is the natural starting point when design concepts are shaped (Blanchard and Fabrycky, 2014). They are furthermore often modified throughout the design process (Almefelt et al., 2006). Fulfilment of the design criteria can be confirmed with analytical models and practical tests (Blanchard and Fabrycky, 2014), but, depending on types of criteria, also by qualitative judgement. Design criteria can furthermore be of different nature and have different roles in the design process.

The different design criteria employed in this thesis, and how they and their types and their combinations are structured, and what their essential features are, is described in Table 2 and Figure 4. These descriptions, aimed at supporting conceptual design, include Pahl´s et al., (2007) definition of Demand and Wish, as well as Suh´s (1990) definitions of Functional Requirements (FRs) and Constraints (Cs). It furthermore includes and distinguishes between quantitative and qualitative criteria.

Table 2. Types of design criteria.

Type	**Definition**	**Comment**
Demand	A criterion that must be met under all circumstances, the solution is otherwise unacceptable (Pahl et al., 2007).	Pahl et al. (2007) use the term requirement to denote what is called criterion in this thesis.
Wish	A criterion that should be considered whenever possible, perhaps with the stipulation that it only warrants a small cost increase (Pahl et al., 2007).	See comment above.
Functional requirement	A criterion used to define a design objective. Established from the functional needs that the product or process must satisfy (Suh, 1990).	Input to the design synthesis process – requires a design solution.
Constraint	A criterion that represents a restraint on an acceptable solution (Suh, 1990).	
Quantitative criterion	A criterion that is numerically quantifiable, such as mass, power, flow, etc. (Pahl et al., 2007).	Analytical means can be used to evaluate fulfilment.
Qualitative criterion	A criterion that is non-numerically quantifiable, such as, e.g., look and feel (Ulrich and Eppinger, 2012).	Human judgement is needed for evaluation.

The combinatorial space of the criteria is illustrated in Figure 4. Eight different combinations are possible, e.g., a functional, qualitative demand or a constraining, quantitative wish etc.

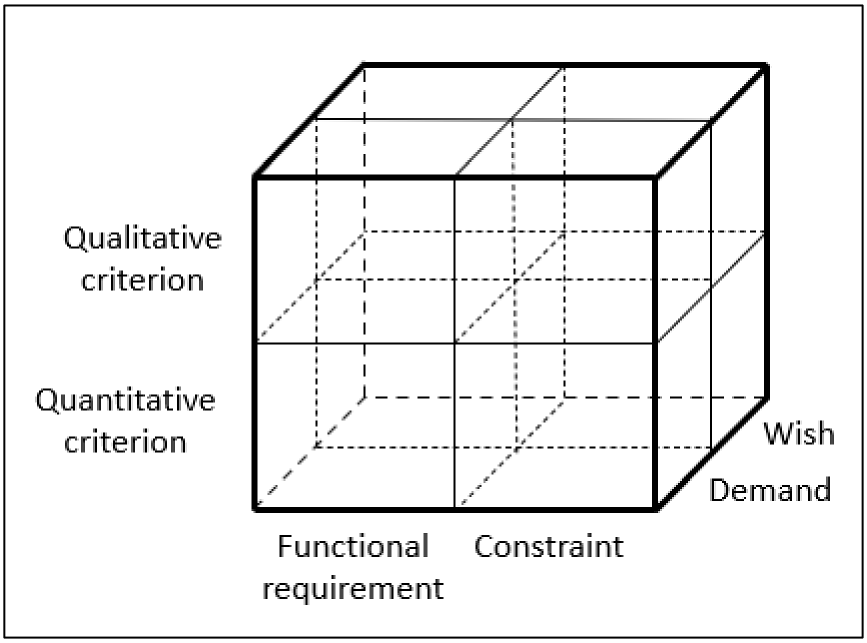


Figure 4. The eight possible combinations of criteria.

2.1.2 Creative methods for synthesis

Design alternatives can be generated using various creative methods as described by different authors. In the 6-3-5 method (Pahl et al., 2007), keywords characterizing different solutions are generated by a group of ideally six participants. Brainwriting, described by Linsey et al. (2011), is a closely related method, in which handwritten sketches are used instead of keywords. The Gallery Method (Pahl et al., 2007), is another technique to promote creativity, in which sketches are posted on a wall to inspire new ideas. Other creative and intuitive methods can be found both in Ulrich and Eppinger (2012) and in Pahl et al. (2007). They can also often be combined to further stimulate creativity (Linsey et al., 2011). Brainstorming, conceived by Osborn (1953), is a method where participants generate ideas by retrieving information from memory and adapting it to the problem at hand. The process is often carried out in a team where ideas can be combined, but it can also be carried out as an individual activity (Ulrich and Eppinger, 2012).

2.1.3 Systematic methods for synthesis and analysis

Pahl et al. (2007) and Ulrich and Eppinger (2012) provide elaborate descriptions of systematic methods for generation of concept alternatives. Examples are the Morphological Matrix (MM) (Pahl et al., 2007), analysis of natural systems (biomimicry), comparison with existing products, and interviews with lead users. Pugh has proposed a matrix for relative evaluation (Pugh, 1996; Pugh 1990).

Systematic solution generation driven by product functionality is mentioned by many scholars, e.g., Hubka (1982, 1988), Pahl et al. (2007), Pugh (1995), Roozenburg and Eekels (1995), Suh (1990), Ullman (2017) and Ulrich and Eppinger (2012). Function-Means (F-M) decomposition (Hubka and Eder, 1988), and MM, introduced by Zwicky and reported by Pahl et al. (2007), are two examples of such synthesis methods. In the F-M model, Functional Requirements (FRs) are connected via causal relations to means, i.e., Design Solutions (DSs). A method similar to F-M solution generation is the Enhanced Function-Means (EF-M) decomposition/modelling (Andersson et al., 2000). Like the F-M model, the EF-M model is a graphical representation of the axiomatic design equation, but it contains more information than the former. The EF-M tree has the same relations as the F-M tree, but it also includes further dependencies. Examples are relations to constraints, influences of and interactions between items, and partial fulfilment of requirements or constraints (see Figure 5). The relations stating influence of and interaction between items can be used for matrix-based analyses of the structure model, that is, based on design structure matrices and axiomatic design matrices. EF-M structures can thus be modelled and used for functional coupling analysis and to explore alternatives in their design space. Such activities can be supported by the software tool Configurable Component Modeler (CCM) (COPE Sweden AB, 2021). This is also demonstrated by Müller et al. (2019).

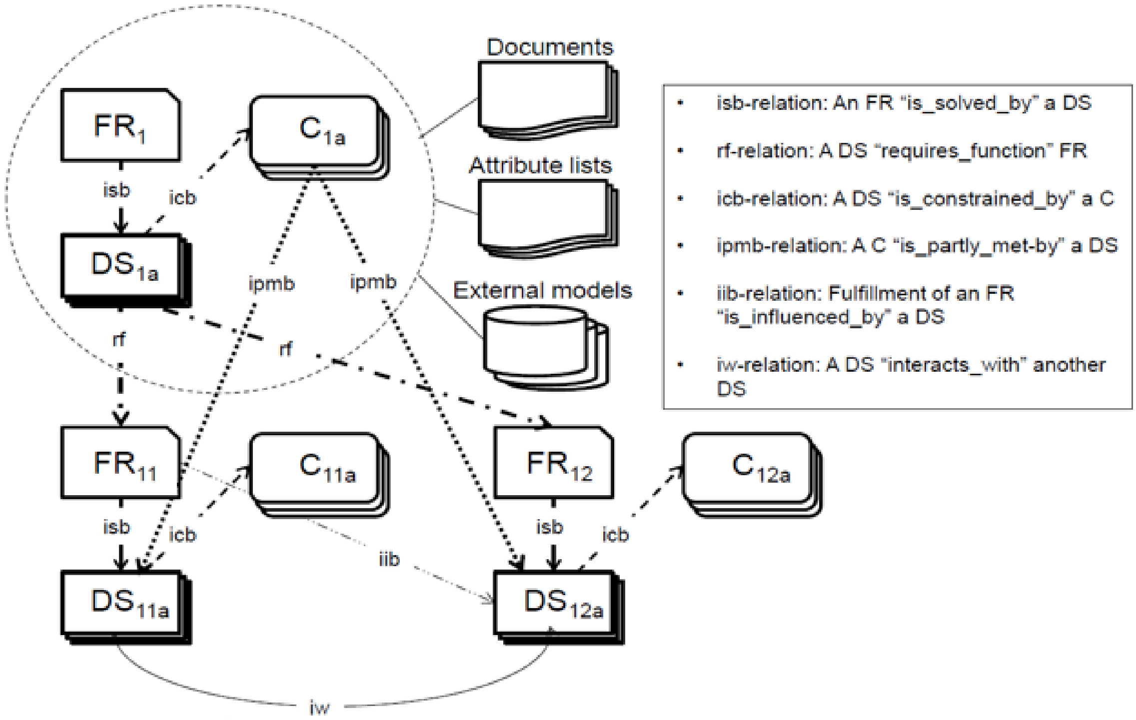


Figure 5. The EF-M model (Johannesson and Claesson, 2005).

Testing and quantitative analysis, e.g., calculations and simulations, are preferred methods when evaluating solutions since they minimize subjectivity. When driving criteria are of a qualitative nature, human judgement may however be the only option. It is also needed when comparing total criteria fulfilment of different alternatives. Then tools like the selection chart by Pahl et al. (2007), the Pugh matrix by Pugh (1996), and the evaluation matrix, also known as the Kesselring matrix (Pahl and Beitz, 1996), may be useful supports. New solutions can also be created by combining concepts when evaluating using the Pugh matrix.

2.2 Lean product development

The pioneering scientific paper describing LPD is the one by Ward et al. (1995), and the concept has been further described by Morgan and Liker (2006), and Ward (2009). These writings are based on observations made by North American researchers at Toyota Motor Corporation in Japan. Ward et al. (1995) describe the set-based concurrent engineering approach in which multiple solutions are explored to find the best design solution. They also describe how design decisions are made as late as possible in order not to unnecessarily constrain the possibilities in the product realization process, which Morgan and Liker (2006) explain as a socio-technical system. In Ward (2009), the Knowledge Value Stream (KVS) and the Product Value Stream (PVS) are described as two essential components of the Toyota Product Development System.

The KVS is an organization's gradual build-up of knowledge about its products, associated technology, customer needs and production technology etc., that is, everything needed to realize the product. This knowledge is precious and therefore needs to be preserved and further developed for future needs. The PVS is the realization process of the actual product.

Another central concept in LPD is Set-Based Design (SBD), which is described in the next section.

2.2.1 Set-based design

In product development, important decisions are often made early in the design process, when the problem at hand is still not well understood. The selected solution candidate is then iteratively improved until it fulfils all necessary criteria. This procedure is known as Point-Based Design (PBD) (Ward et al., 1995).

Set-Based Design (SBD) (Ward and Sobek, 2014), is in contrast characterised by the following three principles:

- Map the design space.
    - Define feasible regions
    - Explore trade-offs by designing multiple alternatives
    - Communicate sets of possibilities

- Integrate by intersection.
    - Look for intersections of feasible sets
    - Impose minimum constraints
    - Seek conceptual robustness

- Establish feasibility before commitment.
    - Narrow sets gradually while increasing detail
    - Stay within sets once committed
    - Control by managing uncertainty at process gates

Contrary to PBD, this means that a whole space of solutions is investigated instead of only one or a few, and inferior candidates are successively eliminated as the designer's knowledge and understanding of the problem grows. The solution space is gradually reduced too, and the remaining solution, by default then assumed to be superior to the others, is then further developed into a working product.

Substantial work has been done to develop SBD since the concept was first proposed. Malak and Paredis (2010) and Rapp et al. (2018) demonstrate the benefit of generating sets of solutions variants. Specking et al. (2018A) use Set-Based Design as a basis for exploration of the design space of solution variants. Several other attempts have been made to model the solution space of a Set-Based Design process. Paulain et al. (2018) suggest the use of surrogate models to illustrate the design space with a two-phase algorithm together with quantitative methods to support a parametric SBD process. Unglert et al. (2016) present a model for Set-Based Concurrent Engineering of a reconfigurable system by generating design candidates using a computational design synthesis. Malak and Paredis (2010) argue that qualitative models lack fidelity to compare similarly performing concepts and suggest the use of parameterized design sets to model the solution space with quantitative data. Strickland et al. (2018) have developed a process to create a design space for surface vessels based on quantitative data. Lange et al. (2019) propose support of SBD in early phases of PD by simplified models of crashworthiness based on quantitative data. Levandowski et al. (2014) use organs/function carriers (Hubka, 1988) to develop a platform based on FRs, with DSs to support Set-Based Concurrent Engineering. Qureshi et al. (2014) present a model based on interval analysis to find robust solutions and consider variations and design objectives. Raudberget et al. (2015) suggest a new methodology for modelling, assessing, and reducing the architectural design space through SBD. Georgiades et al. (2019) analyse, simplify, and narrow the problem space by combining optimization methods and SBD to further improve the most feasible designs. The method, which is too comprehensive for this work, permits human judgement in the process. Further reading can be found in Toche et al. (2020) and Specking et al. (2018A), who have investigated descriptions of SBD in various publications.

Specking et al. (2018A) describe a well-developed methodology based on a cyclic decision process at the system level that uses model-based systems engineering and SBD to explore the design space. Small et al. (2019) suggest a model to create and evaluate designs for military applications which employs a comprehensive parametric model implemented in a spreadsheet software.

The framework used by Small et al. (2019) for integrated trade-off analysis is evaluated by Specking et al. (2019), who find that it adequately explores the trade-off space and identifies optimal solutions. The focus in Small et al. (2019) is on solution variants generated by varying the parameters describing the product, and not on design alternatives with principally different solutions.

2.2.2 Causality and trade-offs

Reusable knowledge (Ward, 2009) and visual alignment (Morgan and Liker, 2006) are two important ingredients highlighted in the domain of Lean Product Development (Ward and Sobek, 2014), of which SBD is a part. Plots of results from product testing can provide insights which are otherwise difficult to arrive at, like trade-offs between entities or design limits that should not be exceeded, as well as internal system dependencies. Relationships can be visualized in causal diagrammes to increase the understanding of mutual dependencies of product criteria (Gustafsson et al., 2016). The impact of one entity on another is shown by an arrow and a plus or a minus sign to indicate how a change in the first entity numerically influences the other.

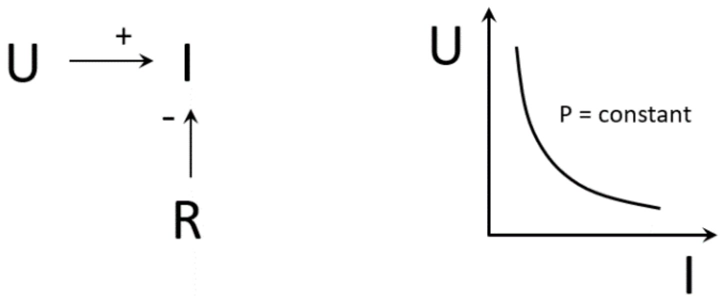


Figure 6. Ohm's law, U = R*I, illustrated with a causal diagramme to the left and with a trade-off curve to the right. I = current, P = power, R = resistance, and U = voltage.

Figure 6 shows how causal diagrammes and trade-off curves can be used to visualize knowledge and thereby make it accessible in an alternative way to mathematical expressions.

In product development, solution concepts are often subject to extensive testing. The results can then be visualized using different types of curves to reveal dependencies (Pugh, 1996) between parameters and trade-offs, and limits of the design space.

Trade-off curves and causal diagrammes are used to analyse and describe products rather than to create new concepts. However, once they have been drawn, development engineers can use them to study how variations in individual product entities influence the whole concept. Dependencies between internal properties, identified and modelled in EF-M structures, is useful as input to causal diagrammes and trade-offs, which can in turn be used to balance constraining criteria. Causal diagrammes can further be used to gain a deeper understanding of assumed functional couplings.

The extended causal diagramme described by Gustafsson et al. (2016) is a combination of a causal diagramme and curves as depicted in Figure 12. This type of visual tool is easy to understand. It can be quickly introduced in an industrial firm and used without any need for external support (Gustafsson et al., 2016).

Malak and Paredis (2010) describe how Pareto fronts can be set up with data and used to create and evaluate design variants. It is furthermore possible to increase resilience in the design process by utilizing a set of solutions not only to identify the optimal candidate, but also to vary data in feasible regions to reflect changing requirements (Rapp et al., 2018). Specking et al. (2018A) use SBD as a basis to generate sets of solutions with an integrated trade-off analysis framework, and they provide a foundation for implementation of SBD through space exploration and model-based systems engineering.

2.3 Axiomatic design

Axiomatic Design (AD) is based on the following two axioms that predict the goodness of a design solution:

(1) The independence axiom: Maintain the independence of functional requirements (FRs)

(2) The information axiom: Minimize the information content (where information is a measure of system complexity) (Suh, 1990)

Suh (1990) has formulated theorems and corollaries based on these axioms and other fundamental knowledge. These can be used by development engineers to find design solution (DS) alternatives, denoted design parameters (DPs) in AD, that fulfil the two axioms as well as possible. In the design equation of AD, FRs are linked via the Axiomatic Design Matrix to their realizing design parameters (DPs). In this way a system´s internal functional dependencies can be detected. The equation and the matrix are the basis for the evaluation. A relative estimate of a system´s information content (or complexity) is its number of functional requirements, as each FR must be fulfilled by a DP, which adds to the total system complexity. AD, and in particular the information axiom, is used by Zheng and Xie (2015) who propose a set-based fuzzy axiomatic design (AD) approach to guide the design decision-making process when evaluating concepts. Also, Tauhid and Okudan (2007) use a similar approach. Mertens et al. (2021) propose a framework supporting product concept generation and evaluation by providing an accessible conceptualization to overcome the limitations using the so-called Extended Axiomatic Design. Delaš et al. (2018) propose a methodology that consists of four steps including to determine the possible violation of the Independence Axiom to evaluate design concepts.

3 Research approach

The objective of Engineering Design (ED) is to develop, manufacture and place a product on the market with a positive economical return. Morgan and Liker (2006) describe the product realization system as a socio-technical system connecting people, process and tools, and technology. The simultaneous involvement of people, processes and technology makes this system complex, since problems related to technology, economics, human behaviour, management, and organisational aspects need to be handled in an integrated manner. This is in line with Ulrich and Eppinger (2012), who highlight the importance of team interaction in this kind of environment. The interaction between members of a design team is a complex process with many parameters (Yin, 2009). Blessing and Chakrabarti (2008) as well as Pugh (1996) emphasise the multi-disciplinary nature of ED processes. Such processes may involve both objective and subjective criteria, and no single right answer may exist. Depending on the characteristics of design problems, different ED processes are likely to differ from each other.

Research in ED, as well as ED activity itself, is concerned with open-ended problems (Pedersen et al., 2000). Solutions of such problems must, to a large extent, rely on observations by humans. It will then be difficult to draw purely deductive conclusions, so inductive conclusions will most likely dominate.

The above-described nature of ED calls for ED research methods that work for a multitude of design approaches in different technological areas. Validation in this broad context is difficult but can, to some extent, be made using objective measures. Fulfilment of subjective criteria calls for subjective judgment when validating results.

The research focus in this thesis is on introduction of LPD, particularly on methods to introduce and support SBD. This is explicitly expressed by the research questions presented in the Introduction chapter.

For studies of the introduction of LPD in industrial firms, case study techniques according to Yin (2009) are suitable. These are observative, where researchers collect data and draw conclusions. Other interesting approaches are the Research Methodology (DRM) (Blessing and Chakrabarti, 2008), and the Scientific Work Paradigm (SWP) of Jørgensen (1992). In both DRM and SWP, researchers may be involved in the studied processes. This characterises action research approaches (Oosthuizen, 2002).

3.1 Design research methodology

Blessing and Chakrabarti (2008) have created the Design Research Methodology (DRM). In this methodology, researchers study aspects of a design process and develop supporting means aimed at improving the design work. DRM has a clear focus on acquiring knowledge on how to be more successful in designing products. The design of industrial products is a complex and multi-faceted activity. Blessing and Chakrabarti (2009) have observed that several different methodologies, not geared towards product development, have been used to carry out research in this domain. This has caused a risk of poor validity of the results. DRM was created to minimize this risk and provide a reliable method dedicated to research in product development. The main components of the DRM framework are shown in Figure 7.

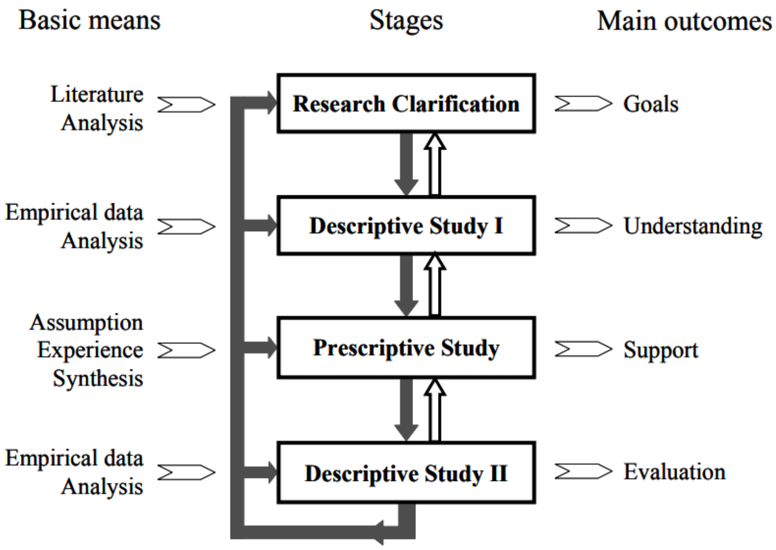


Figure 7. The DRM framework from Blessing and Chakrabarti (2009).

In the research clarification, the research work is prepared and clarified. The researchers set the goals and focus of the research. Research questions and hypotheses are formulated, and other preparatory measures are undertaken. In the Descriptive Study (DS) I, literature relevant for the stage is reviewed and the current situation is investigated to achieve a better understanding of what has an impact on the situation that we want to improve. In the Prescriptive Study (PS) stage, supporting measures of the current situation are developed based on the findings from DS I. Also means and plans on how to evaluate these measures are developed. In DS II, the suggested measures from the PS stage are evaluated, and necessary improvements of the supporting measures are suggested (Blessing and Chakrabarti, 2009). As indicated by the arrows in Figure 7, iterations can be made between the different stages in the DRM model to develop better support in the PS stage and evaluate this in the subsequent DS II stage.

3.2 Scientific Work Paradigm (SWP)

In his method, Jørgensen (1992) describes two different research approaches (see Figure 8), a hermeneutic in the left path and a more positivistic in the right path, both resulting in new scientific knowledge which can be transferred for adaption and implementation.

In the left path, the research process starts with case studies, where design problems are identified and studied. The analysis results in diagnoses that clarify problem issues such as needed activities and method support for different design process tasks. In the next step, these are input to a synthesis of possible solution approaches which results in new scientific insight to be used in practice. The right path starts with existing theories as a base for synthesis and modelling. After analysis and validation, new scientific insights are transferred to be used in practice.

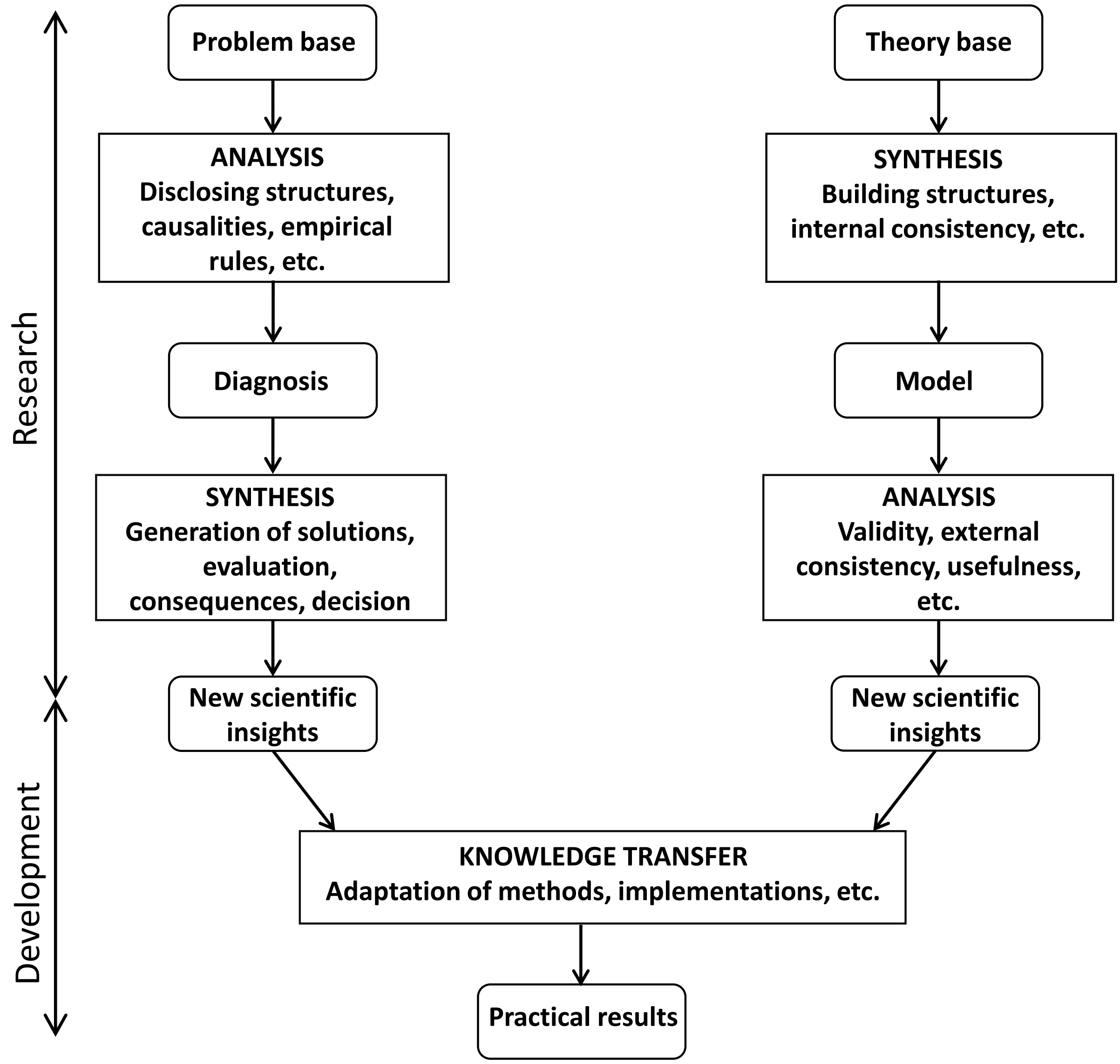


Figure 8. General layout of the Scientific Work Paradigm (SWP) (after Jørgensen, 1992).

3.3 Action research

Action research is an approach where the researcher participates in the action subject to research. This contrasts with many other approaches, where the researcher is required to have a detached role as an observer (Oosthuizen, 2002). Action research is done in a cyclic manner. The researcher participates in an action part of a process and collects data to be analysed from the same process. The action research cycle can be described as in Figure 9.

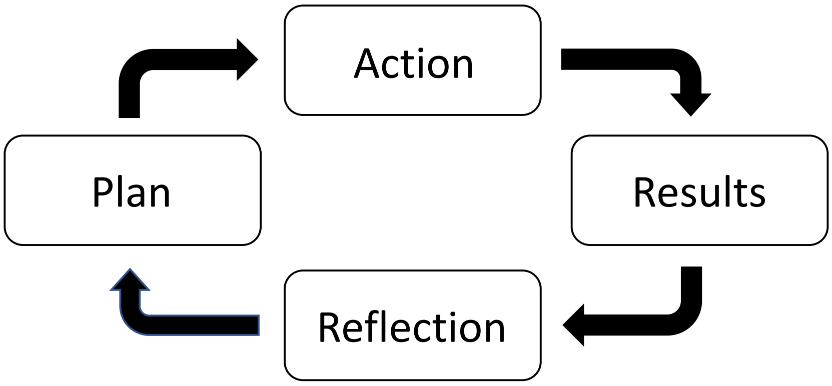


Figure 9. The Action research cycle (Oosthuizen, 2002).

Action research is suitable for exploratory research to test solutions to practical problems and gain knowledge at the same time. Action research shall be seen as a means for building transferable knowledge rather than generalizable knowledge.

3.4 Case study methodology

A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context. The boundaries between phenomena and context are often not clear. The case study methodology is suitable to study technically distinctive situations in which there will be many more variables of interest than data points. To support the results of a case study, multiple sources of evidence are used (triangulation). As data is collected, the results of a case study shall support a converging conception of the phenomenon studied. The study, data collection and analysis are often guided by a theoretical proposition developed prior to the study.

A case study can be a multiple study, investigating more than one case of similar or contrasting nature, or it can be a single case study, investigating only one case.

Some common components of a case study are:

1. Research questions to be answered.
2. A study proposition (like an anticipated result of the study).
3. Unit of analysis.
4. Logical links between data that will be collected and the anticipated result of the study.
5. Criteria on how to interpret the collected data.

Prior to a case study, existing literature is often consulted to provide a framework for a theoretical understanding. The framework can be of help when interpreting the collected data, and when formulating the study proposition. The main steps of a case study are described in Table 3.

Table 3. Steps of a case study (Yin, 2009). They are often carried out in an iterative manner.

Step	**Description**
Plan	Identify research questions or other incentives to carry out a case study. Compare case study methods to other methods and understand their limitations before choosing method.
Design	Define cases to be studied and unit of analysis. Develop underlying theories and propositions to the study. Select case study type: Single, multiple, holistic, or embedded. Define procedures to maintain quality of the study.
Prepare	Refine skills and repeat procedures of the case study approach selected. Set up a case study protocol. Conduct a pilot study. Sort out risks that the study may be intrusive and obtain permission to carry out the study.
Collect	Collect data according to the case study protocol. Use multiple sources of data. Save data in an appropriate and secure way. Assure a chain of evidence from data to results.
Analyse	Use analytical techniques to analyse data. Compare with theory and explore rival explanations. Display data.
Share	Design textual and visual material to communicate the results to the expected receivers. Allow for receivers to draw their own conclusions from the material. Review and redesign the material until acceptable.

In both DRM and SWP, researchers will investigate contemporary phenomena to be able to answer Why and How questions. This is evident in the descriptive steps of DRM and in the analysis step in the left path in SWP. The case study technique can be used as part of both DRM and SWP to answer these questions.

3.5 Methods for data collection

Data, like evidence, can be collected through observations in meetings and workshops, questionnaires answered in workshops, records in computer systems, documents, interviews and process mapping. Different methods need to be used depending on evidence type, given possibilities and the need for information. This applies to case studies with or without combinations with DRM and SWP.

3.6 Methods for validation of results

Since research in ED involves both objective and subjective judgment, validation needs to be carried out in a different way compared to areas where results can be judged on an objective basis. Validation can involve the opinion of different stakeholders, whether the output of the research is useful or not. A useful result is a good sign but not sufficient to justify full validation of it. To cope with this problem, different scholars have made frameworks that fill the gap. The one of Cross (2007), with the five different criteria described in Table 4, is used to validate the research. These are normal criteria for good research in any discipline.

Table 4. Criteria of what is valid design research according to Cross (2007).

Criterion	Explanation
Purposive	Based on identification of an issue or problem worthy and capable of investigation.
Inquisitive	Seeking to acquire new knowledge.
Informed	Conducted from an awareness of previous, related research.
Methodical	Planned and carried out in a disciplined manner.
Communicable	Generating and reporting results that are testable and accessible by others.

An example of an approach that is somewhat more detailed is the one of Pedersen et al. (2000). In this framework, applied theory, sample applications of the theory, and usefulness of the developed theory, are evaluated. In this way, an overall validation of the conducted research is obtained. There is a clear emphasis on the usefulness of the results, as evidence of their validity. The framework is divided into six steps and displayed as a model named "The validation square" (see Figure 10).

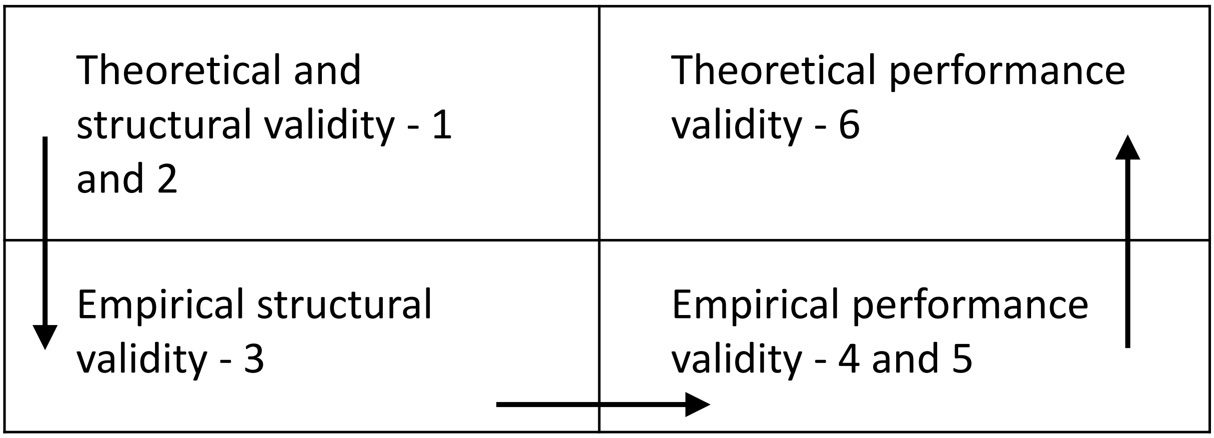


Figure 10. The validation square. Adapted from Pedersen et al. (2000).

The six steps of Pedersen´s et. al (2000) method is:

1. Accepting the individual constructs constituting the method.
2. Accepting the internal consistency of the way the constructs are put together in the method.
3. Accepting the appropriateness of the example problems that will be used to verify the performance of the method.
4. Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s).
5. Accepting that the achieved usefulness is linked to applying the method.
6. Accepting that the usefulness of the method is beyond the case studies.

In case study methodology according to Yin (2009), validation can be divided into four categories. These are construct validity, internal validity, external validity, and reliability. Construct validity can be achieved by using multiple sources of evidence, chains of evidence and key informants to confirm results. Internal validity, often important in explanatory case studies, can be obtained by carrying out pattern matching, explanation building, addressing rival explanations and using logical models. External validity is related to the generalizability of the result, i.e., applicability beyond the case studies. This type of validity can be achieved using theory in single-case studies and replication logic in multiple-case studies. According to Yin (2009), reliability in case studies is achieved by having a case study protocol and developing a case study database.

A fourth framework for validation of research results in ED is the one by Buur (1990), who has proposed the following criteria:

Logical verification:

- Consistency: no internal conflicts between individual elements (e.g., axioms) of the theory.
- Completeness: all relevant phenomena observed previously can be explained or rejected by theory (i.e., observation, from literature, industrial experience, etc.).
- Well-established and successful methods in agreement with theory.
- Cases (i.e., particular design projects) and specific design problems can be explained by means of the theory.

Verification by acceptance:

- Statements of the theory (axioms and theorems) are acceptable to experienced designers.
- Models and methods derived from the theory are acceptable to experienced designers.

3.7 Applied research approach

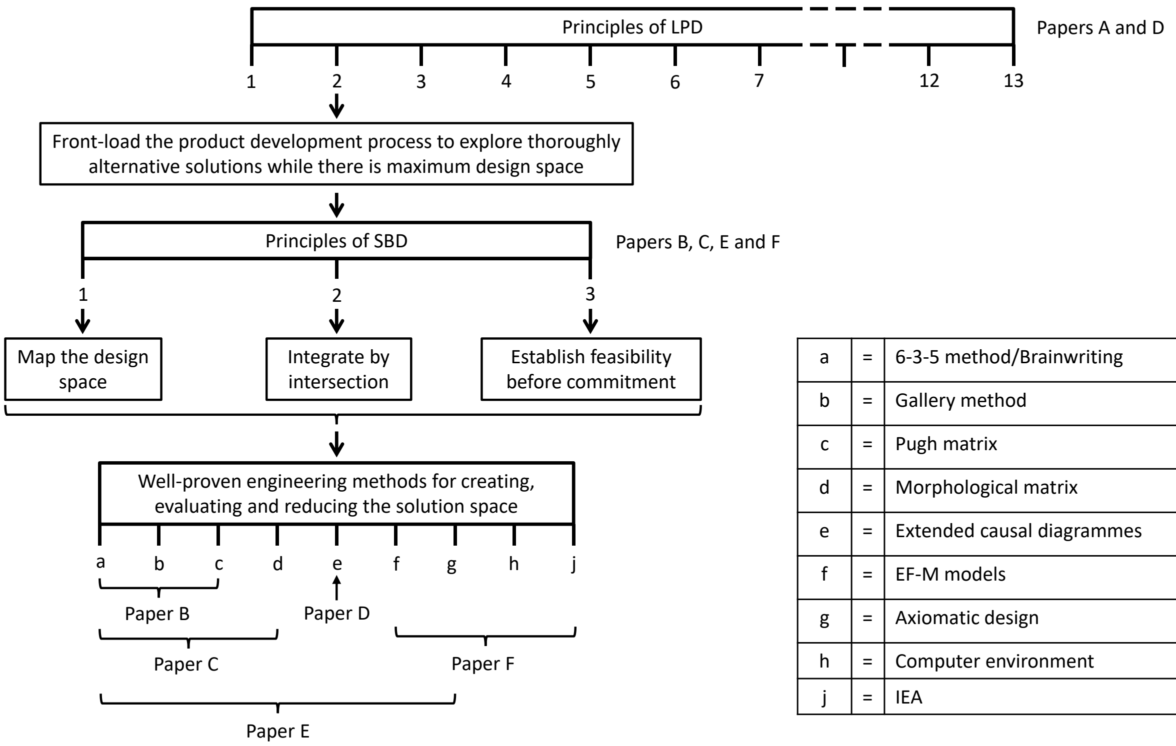
The research described in this thesis is conducted using three major approaches. One basic component of all of them is multiple case studies. Two or more cases are investigated in all three. The approaches are:

- A two-case study.
- DRM combined with multiple-case studies and elements of action research.
- SWP combined with multiple-case studies and action research.

The validation frameworks of Cross (2007), Pedersen et al. (2000) and Buur (1990) have been considered in the different studies.

4 Conducted research and findings

Research conducted in the different projects follows the schedule proposed in the introduction (see Figure 2). The studies presented in this thesis are addressed in the different papers as seen in Figure 11. The position of Paper A is defined in Ström (2013).



a	=	6-3-5 method/Brainwriting
b	=	Gallery method
c	=	Pugh matrix
d	=	Morphological matrix
e	=	Extended causal diagrammes
f	=	EF-M models
g	=	Axiomatic design
h	=	Computer environment
j	=	IEA

Figure 11. Principal positioning of appended papers in relation to lean principles and engineering methods. The 13 principles of LPD are according to Morgan and Liker (2006), and the three principles of SBD are according to Ward et al. (1995). See also Figure 2.

4.1 Paper A - Transformation to Lean Product Development – Approaches at Two Automotive Suppliers

The transformation to a lean product development system was studied at two automotive suppliers of different sizes producing different types of components. The study covers the process from the initial state via the transformation approach, the problems along the way, some early results of the transformation and a comparison between the two firms in this respect.

4.1.1 Introduction

Many automotive industry suppliers use product development (PD) processes divided into phases and gates like the one of Cooper (1994). Even though the latter has been revised over the years to mitigate many of the initial drawbacks, it is still its first version that often prevails. The phase-gate time plan imposes an end date on the project team, which may have to pass gates without fulfilling the requirements of them just to comply with the plan. This is a devious behaviour in which time keeping takes priority over needed knowledge in the PD process. One approach to mitigate the negative effects of the phase-gate process and to possibly shorten development time is to use methods from lean product development (Ward, 2009), which are employed by both firms in the study. In this context the following research questions are proposed:

- How can LPD be introduced at tier 1 suppliers in the automotive industry?
- What are the experiences when introducing LPD at an automotive supplier designing and manufacturing components?

4.1.2 Performed research

The research is a two-case study at Akwel Sweden AB (Akwel, formerly Autotube AB) in Varberg, Sweden, and Kongsberg Automotive AB (Kongsberg) in Mullsjö, Sweden, with internal and external development projects as embedded units of analysis (Yin, 2009). Evidence was collected through observations in meetings and workshops, questionnaires answered in workshops, records in computer systems, documents, and interviews. Validity was achieved by using multiple sources of data, rival framework, comparison between case studies and case study documentation (Yin, 2009).

4.1.3 Findings

The results show that the transformation to lean product development is experienced as positive in both firms. It is demonstrated that this success is due to some of the methods and principles included in the lean product development framework. The transformation is affected by different influencing factors. The nature and impact of these factors for each firm is presented in Table 5.

Table 5. Studied components of the transformation processes at the two firms.

Influencing factor	**Role/Impact at Akwel**	**Role/Impact at Kongsberg**
Lean enthusiast - has a strong belief in LPD. This person promotes LPD in the organization.	The lean enthusiast is the design manager, who promoted the idea of introducing LPD. They tried to create a pull for LPD in the organization.	The lean enthusiast kept the process alive prior to the strategic decision and promoted activities that informed Kongsberg about LPD. They also supported the strategic decision of the management to transform to LPD and encouraged others to follow.
LPD networks - LPD interest groups.	The design manager participated in different LPD networks to evaluate and benchmark other companies. It was valuable to see the big picture and get inspiration.	Design managers of Kongsberg participated in the LPD interest group. The membership in the network provided the company with experience from others trying to adopt LPD.
Coaching programme in production.	The company participated in a national coaching programme to implement lean production. This created an appetite to also introduce LPD.	Lean production had been implemented prior to LPD. The latter was however not inspired by the former, but rather by the lean enthusiast.

Influencing factor	Role/Impact at Akwel	Role/Impact at Kongsberg
Early information - new findings in LPD. Books, seminars etc.	This information was important, as the LPD way of working has in some way changed over time.	This information helped promoters of LPD and others in the firm to understand the advantages of LPD and convinced them to continue promoting it within the organisation.
Strategic decision. At one point the top management of the firm made a strategic decision to adopt LPD.	The strategic decision was made mainly by the design manager and the technical manager. The top manager saw the first step of LPD and went along with the intention and formally approved it.	The strategic decision was made by the top management of the firm. This created the necessary motivation in the organisation, and the promoters of LPD could formalise their ideas.
Education and training - the way individuals are educated in LPD.	Education and training were provided by the academic partners in this research project. Some training in the coaching programme for production could be used in PD.	Solid and reliable partners for education made the members of the organisation believe in the new philosophy of product development.
Change of PD project model, or not.	The project model was not changed but is used as a guiding principle, and it is therefore not an obstacle in the transformation to LPD.	The new project model based on LPD is a clear signal of how managers and project leaders shall run PD projects.
Pilot test of LPD.	Pilot tests of SPS, A3s and Visual Planning were carried out.	The firm ran four test projects in which the new LPD process was used. This provided input to refine it.
Full introduction of LPD.	The firm is comparably small, so the introduction is uncomplicated. The strategy is to create a pull in the organisation for more lean methods.	After the test projects, the new LPD process will be implemented in one division. Further implementation will depend on the experiences from this.
Function for education and refinement of the LPD process.	Education and refinement of the LPD process is carried out in infrequent workshops, but also in shorter dedicated improvement sessions every second week led by the design manager.	This function very quickly accepted the idea of LPD, which supported the promotion of it. This process is more of a push than a pull for new working methods.

A comparison of how different parts of LPD were perceived and used is shown in Table 6.

Table 6. Application of parts of LPD.

Application	Akwel	Kongsberg
Knowledge Value Stream (KVS)	The aim to consolidate knowledge resulted in the testing of A3s and structured problem solving.	The KVS is part of the first phase of the LPD process, and the intention is to close all knowledge gaps before a binding offer is sent to the customer.
Customer Interests or Voice of the customer	To get a better picture of customer interests, all visits to customers are registered in a log together with observations made.	As part of the new LPD process, three to five main customer interests shall be defined for each project.
Structured Problem Solving (SPS) on A3	Training and coaching were carried out as part of the study and gave immediate positive results.	The firm has an internal training course in SPS and robust learning. It took some time to change the minds of the engineers to document and share their deep knowledge.
Visual Planning (VP)	VP is used for both customer projects and internal projects. Planning meetings are	Each product development project that runs according to the new LPD process uses an

Application	Akwel	Kongsberg
	conducted every Monday morning. Afterwards a smaller VP meeting for the design department is held. Some project managers use foldable planning boards that serve as mobile Obeya rooms (Horikiri, 2008).	Obeya room (Horikiri, 2008) where VP is used. The layouts of the boards differ. Visual Planning has not been successful in geographically distributed projects.
Integrating Events (IE)	IE were used on a few occasions to try out this new concept. They were more efficient than the traditional design reviews: At the very first attempt, product design deficiencies were found and corrected at an early stage.	IE are becoming a common practice in projects using the new LPD process. They are used to confirm design convergence and closure of knowledge gaps, and to evaluate and select between multiple solutions to a design problem.
Knowledge Owner (KO)	KOs exist informally in the firm, i.e., no one has yet been formally appointed.	KOs have been appointed in the organisation. There are however different alternatives for their areas of responsibility.
LPD model	The firm uses a self-developed PD model which is now being combined with a KVS.	The new lean-inspired PD model is a clear signal from management on how PD projects shall be run.

4.1.4 Conclusions

From the results and the discussion in paper A, the following is concluded:

- Good communication is a key success factor in PD projects in the automotive supply chain.
- Structured Problem Solving (SPS) is a powerful technique.
- Time must be allocated to adopting knowledge consolidation by means of A3s and SPS.
- SPS and Visual Planning are relatively easy to make feasible. They improve communication and make work more efficient, thereby freeing up time to adopting additional LPD methods such as knowledge consolidation and reuse.
- LPD, as presented in this paper, supports knowledge build-up and reuse.
- The roles of the Knowledge Owners in the two firms were difficult to define with respect to organisational position and detailed responsibility.

4.2 Paper B - Development of a methodology to implement set-based design in a day

The purpose of the research is to improve engineering design processes in industry by supporting them with Set-Based Design (SBD). The objective is to develop a methodology to introduce Set-based design within a day, thereby facilitating an easier introduction of the methodology.

4.2.1 Introduction

Some authors claim that SBD and related practices from Lean Development are four times more productive than traditional development models (Ward and Sobek, 2014; Morgan and Liker, 2006). SBD is however challenging to introduce for several reasons. Another issue, not described in the literature, is what methods and strategies to use to generate the multiple alternatives that are of vital importance in SBD. Furthermore, there is little guidance on how to deploy SBD in practice.

The purpose of this research has been to improve engineering design processes in industry by supporting them with SBD. The objective is to develop a methodology to introduce SBD in one day, thereby facilitating an easier implementation of the methodology.

4.2.2 Performed research

The research process described in this paper followed the Design Research Methodology (DRM) for the development of design support (Blessing and Chakrabarti, 2009). The process was iterated between stages, descriptive study II and prescriptive study III until the result was satisfactory. Each descriptive study was carried out as a case study. Each prescriptive study included facilitation by the researcher in an action research fashion.

4.2.3 Findings

A new simplified approach coined Instant Set-Based Design (ISBD) was found feasible to overcome the abovementioned problems. In ISBD, the Set-Based Design process is complemented with methods for creative synthesis and design evaluation. In total 45 experienced designers have tested the method on real mechanical design problems. It was perceived easy to understand and was well received by the designers. The introduction of it was less cumbersome compared to the full version of SBD. The conclusion is that the developed method makes it easier to introduce parts of SBD with good results. A result is that the firms which participated in the studies can use the methodology without subsequent support from the researchers. The different steps in the ISBD methodology are shown in Table 7.

Table 7. The ISBD steps in paper B.

Step	Description
1	A brief introduction to SBD, the 6-3-5 method (Brainwriting), the gallery method, and the inverse Pugh matrix. The workshop leader gives a short lecture on these subjects.
2	Presentation of the design problem. All participants should be well-informed about the problem at hand to be able to contribute to its solution. Previous designs, physical artefacts, lists of requirements, and descriptions of targeted users etc. can be used.
3	Solution generation by the 6-3-5 method (Brainwriting). The workshop participants are typically seated around a table and equipped with A3 sheets, pens, and the description of the design problem.

Step	Description
4	Presentation of the concepts by posting them on a wall, which is the start of the gallery method.
5	Elimination of solutions by identifying problems with them. Issues were written on Post-it notes and solutions with several problems were removed and stored in the design repository.
6	Assigning of the remaining sketches to specific participants for further development. The participants are typically seated around the table again and work on improved solutions based on ideas received from the discussions in front of the wall in steps 4 and 5.
7	Posting of the improved solutions and use of the inverse Pugh matrix. Each concept is compared with the datum.
8	Identification of knowledge gaps and ways to bridge them, as evaluation criteria. For each concept in the inverse Pugh matrix, knowledge gaps are identified and tentative measures to bridge them are described. This can be testing, building prototypes, searching for information, and consulting experts etc.
9	Elimination of the least feasible solutions based on the results from the inverse Pugh matrix, knowledge gaps and measures to bridge them.

The Pugh matrix applied includes spotted knowledge gaps for each solution alternative. The matrix was solely used as a tool for eliminating solutions, and not for selecting solutions. For this reason, it was denoted "the inverse Pugh matrix".

A comparison of the features of the ISBD methodology, SBD and traditional PBD is given in Table 8. Inputs to the comparison are the results from the described study in Paper B, resulting in the definition of ISBD in section 5 of Paper B and inputs from Ward et al. (1995) and Sobek et al. (1999).

Table 8. Comparison between Instant Set-Based Design (ISBD), Set-Based Design (SBD) and Point-Based Design (PBD).

Feature	ISBD	SBD	PBD
Starts with multiple design solutions.	Yes	Yes	Yes
Has an integrated creative method to generate multiple solutions.	Yes	No	No
Simultaneously explores the feasibility of multiple design solutions.	Yes	Yes	No
Selects the most promising design solution.	No	No	Yes
Continuously eliminates inferior solutions.	Yes	Yes	No
Fixed specification which describes the requirements of the design.	Yes	No	Yes
Has a design specification based on intervals.	No	Yes	No

Feature	ISBD	SBD	PBD
Iterations to correct failures is a typical means.	No	No	Yes
Convergence is built into the method to reduce sets of designs and arrive at a final solution.	Yes	Yes	No
Early detection of knowledge gaps of design solutions.	Yes	Yes	No
Takes advantage of late design decisions.	Yes	Yes	No
Exploration of multiple solutions on the spot.	Yes	No	No
Explores concepts through testing.	No	Yes	Yes
Facilitates sharing of information, ideas, and knowledge of sets of solutions.	Yes	Yes	No
The process can continue as a true SBD process.	Yes	Yes	No

The results were validated with respect to the criteria in Table 9.

Table 9. Validation criteria, reformulated from paper B.

Criterion	Fulfilment
Does the methodology generate more ideas than the current way of working does? [In accordance with step 4 of Pederson (2000).]	Yes
Do experienced engineers accept the methodology as a new way of working? [In accordance with criterion 6 of Buur (1990).]	Yes
Do experienced engineers accept the results from the new methodology? [In accordance with criterion 5 of Buur (1990) and step 4 and 5 of Pederson (2000).]	Yes
Can the methodology be learned in a day? [In accordance with step 4 of Pederson (2000).]	Yes

4.2.4 Conclusions

The results above lead to the following conclusions:

- ISBD is a feasible methodology for mechanical design problems.
- ISBD is feasible for introducing parts of SBD.
- ISBD can be introduced and applied in one day and was later implemented in the development process at one of the companies.

Besides these, the following conclusion can also be drawn, although it is not mentioned in the paper:

- It is an advantage if the decision to run the workshop is taken by the team manager, and this person also participates in the workshop.

4.3 Paper C - Instant Set-based Design, an Easy Path to Set-based Design

This paper is very similar to paper B, with the difference that the morphological matrix (MM) is introduced to generate concepts to feed the ISBD process.

4.3.1 Introduction

The creative methods used in the studies of paper B generate many sub-solutions. These are possible to combine in several ways to obtain new solutions, but this possibility was not utilised in those studies. In paper C, the MM is therefore added to visualize the possibility to combine sub-solutions.

4.3.2 Performed research

The research process described in this paper follows the Design Research Methodology (DRM) for the development of design support (Blessing and Chakrabarti, 2009). The process is iterated between the stages in the descriptive study II and prescriptive study III. Each descriptive study is carried out as case study, and each prescriptive study includes practical implementation by the researcher in an action research fashion.

4.3.3 Findings

The results described in this paper are very much in line with those in paper B. The addition of an MM in ISBD (see Table 10) gives birth to additional solutions and enables combinations of sub-solutions. This makes it harder though to finish the workshop within an eight-hour day. A firm can however use the methodology without subsequent support from the researchers.

Table 10. The ISBD steps in paper C.

Step	Description
1	A brief introduction to SBD, the 6-3-5 method (Brainwriting), the gallery method, MM and the inverse Pugh matrix.
2	Presentation of the design problem and required functionality of possible solutions. All participants should be well informed about the problem at hand to be able to contribute to its solution.
3	Generation of solutions by the 6-3-5 method (Brainwriting).
4	Presentation of the solutions by posting them on a wall.

Step	Description
5	Collaborative analysis of how each function is realized in each concept.
6	Elimination of solutions by identifying weaknesses. Issues were written on post-it notes and inferior solutions were removed and stored in the design repository.
7	Application of the gallery method to the remaining solutions.
8	Using an MM for all concepts to try to generate more solutions by cross-fertilization.
9	Posting of improved solutions on the wall and comparison of them by means of an inverse Pugh matrix.
10	Identification of knowledge gaps, to fulfil the required functionality, and ways to bridge them.
11	Elimination of the least feasible solutions based on the results from the inverse Pugh matrix.

The results are validated with respect to the criteria 1-5 in Table 11.

Table 11. Validation criteria used in paper C.

Criterion	Fulfilment
Does the methodology generate more ideas than the current way of working in the company? [In accordance with step 4 of Pederson (2000).]	Yes
Do experienced engineers accept the methodology as a new way of working? [In accordance with criterion 6 of Buur (1990).]	Yes
Do experienced engineers accept the results that the methodology generates? [In accordance with criterion 5 of Buur (1990) and step four and five of Pederson (2000).]	Yes
Can the methodology be learned in a day? [In accordance with step 4 of Pederson (2000).]	Yes
Is it feasible to combine creative and systematic methods for concept generation to feed the ISBD process? [In accordance with criterion 1 of Buur (1990) and step 2 of Pederson (2000).]	Yes

4.3.4 Conclusions

The conclusions from paper B still apply, even though the conclusions from paper C are expressed slightly differently. The conclusions from paper C are that:

- instant Set-Based Design (ISBD) works well applied to mechanical design problems in an industrial environment,
- ISBD can be used to start the implementation of Set-Based Design and

- SBD helps industrial firms to implement Set-Based Design.

It can be added that the introduction of an MM in ISBD makes it possible to also conclude that it:

- facilitates the combination of sub-solutions,
- gives birth to solutions in addition to those in paper B, but
- makes it difficult to complete the ISBD method in one day.

These (last three bullets) are the results presented in paper C. They were however not taken into consideration when drawing the conclusions presented in the same paper.

4.4 Paper D - Unveiling fundamental relationships in industrial product development

Identification and clarification of relationships between product properties is fundamentally important in industrial product development. This process is however frequently perceived difficult. The presented research aims at clarifying if a visual tool can provide help in this work.

4.4.1 Introduction

When redesigning a product, the design team must understand how the product works at present. This means how different parts interact and impact properties of the product, the physics behind this and what is known, and - most importantly - not known and understood. Due to the properties of the human brain, visualization is often useful both to create an overview of something as well as to highlight details and connections in a larger pattern. This paper proposes a technique and a visual aid for product developers which combines several existing tools to accomplish this.

4.4.2 Performed research

The setup is a multiple case study (Yin, 2009) of EM design with two main industrial design cases. The research process was inspired by the Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009). An initial literature study clarified that there was a lack of research results in this area, even though the support is mentioned in Ward (2009). A descriptive study was performed to understand the needs of the firms in the case study. This was followed up with a prescriptive study where the suggested support was tested. The results of the tests were documented in a second descriptive study.

4.4.3 Findings

It was found that causal diagrammes could be successfully combined with curves to illustrate how different parameters impacted the properties of the product. Parameters could be categorised into selling point properties, internal properties of the product and customer application properties, see Figure 12. The case study firms were able to use the methodology without the support from researchers.

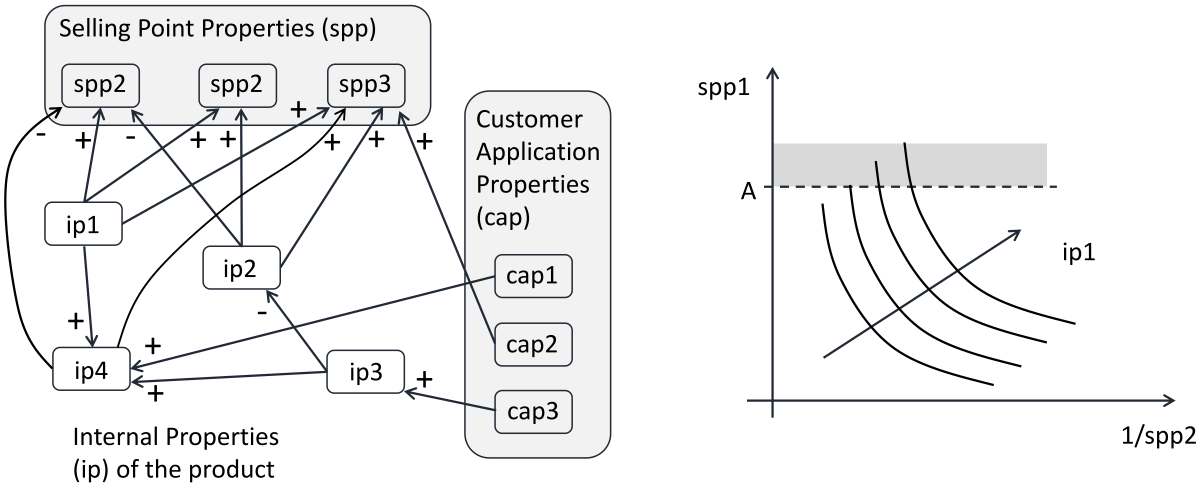


Figure 12. The simplified layout of a causal diagramme used in one application in paper D. A trade-off curve for the properties spp1 and spp2, and the impact of ip1. The diagramme also includes a limit curve, since the level of ipp1 is not allowed to exceed A.

The results were validated with the criteria described in Table 12.

Table 12. Validation criteria used in paper D.

No.	Criterion	Fulfilment
1	Does the methodology create a better understanding of the product than the current way of working in the company does? [In accordance with step 4 of Pederson (2000).]	Yes
2	Do experienced engineers accept the methodology as a new way of working? [In accordance with criterion 6 of Buur (1990).]	Yes
3	Do experienced engineers accept the results that the methodology generates? [In accordance with criterion five of Buur (1990) and step four and five of Pederson (2000).]	Yes

4.4.4 Conclusions

The result of the conducted research fulfils the success criteria in Table 12, since:

- The extended causal map offers a better understanding of the product in the sense that it reveals previously unknown relationships (in line with criterion 1).
- It encourages the user to quantify relationships and describe them as curves in the causal diagramme (in line with criterion 2).

- The combination of causal diagrammes and trade-off curves is a powerful and simple tool that can unveil fundamental relationships between properties in industrial product development (in line with criterion 1).
- The use of the methodology helped both companies in the study to gain new knowledge about critical aspects of their products. One firm used knowledge from the causal map to communicate performance properties of its products both internally and in the form of an external sales tool (in line with criterion 1).
- The methodology is rather easy and quick to introduce, and it does not require the researchers to be present after its implementation. It was quickly accepted as a new way of working in the firms, and the results from the applications were perceived as highly relevant by experienced engineers (in line with criteria 2 and 3).
- The scientific approach applied in this research secures the reliability and validity of the findings. The results are validated with respect to the criteria in Table 4. The results add new knowledge to the scientific literature.

4.5 Paper E - Efficient Set-Based-inspired generation and elimination of alternative design concepts

This paper presents an approach to a Set-Based-inspired concept development process for generation, evaluation, and reduction of a solution space of alternative concepts, i.e., step one in the process presented in paper F (see Figure 15). Also, the aspect of how to introduce the process in an industrial environment was investigated and is discussed.

4.5.1 Introduction

An early step when developing a new product is to establish a population of potentially feasible designs by investigating a relevant solution space. Firms who produce parameterised EM products often vary governing parameter settings to create new variants. When this possibility is exhausted, the next step is to consider new and principally different design alternatives. Another reason to do this can be the appearance of a new technology. There is however no single method that can handle all tasks in the concept development process. Different tasks require different techniques, e.g., specification, synthesis, analysis, and decision making. Gericke et al. (2020) argue that instead of continuing to develop new methods, it is worth combining and refining already existing ones in a meaningful way. Pahl et al. (2007) also highlight the advantage of combining methods for generating alternative concepts. In industrial case studies (Ström et al., 2016B) it has become apparent that firms often lack knowledge about available methods for generation of solution alternatives, and combination of them in a good way.

How to compose, quickly introduce and apply such an efficient combination of methods for collaborative development of feasible design alternatives is the focus of this paper.

4.5.2 Research questions

The following research questions are now formulated:

- How can existing methods and tools be combined to facilitate an efficient process for synthesis, evaluation, and reduction of a solution space of design alternatives?
- How can methods facilitating efficient generation, evaluation, and reduction of solution spaces be quickly introduced, applied, and tested in a collaborative environment?

4.5.3 Performed research

The approach in paper E has been to support the different tasks in the concept development process, i.e., specification, synthesis, analysis, evaluation, and elimination, with existing known methods, and combine them in a seamless process. The scope of this is to include PD of new products based on needs as well as improvements of existing products.

The result is an eight-step procedure which was verified and validated in two different industrial cases: an oil tube in the engine compartment of an automobile, and a sliding door mechanism. This shows its applicability and validity when designing EM products in industrial settings.

In the case of the oil tube, the development engineers:

- specified the design task by supplying documents describing the application and examples of solutions,
- were interviewed by the researchers to get additional input to the requirements specification,
- commented on and evaluated solutions from competitors,
- participated in workshops (same as in paper F) to collect data and test the method,
- built and tested prototypes to verify that the final design fulfilled the requirements and
- evaluated the outcome of the process.

The sliding door case was run as a student project in a master programme course at Chalmers and resulted in a new type of mechanism to move the doors. It was carried out in close interaction between the students and the company in question. The product development method suggested in this thesis was later applied by the researchers on the same case, with the same outcome regarding synthesis and analysis of design solutions as in the student project.

At the firm with the sliding door case:

- development engineers supported the specification of the design task by suppling a requirements specification and examples of a previous design,
- the development and support engineers were interviewed to get additional input to the requirements specification,
- the development engineers provided feedback on product planning requirements, stakeholder analysis and competitor analysis,
- the internal test lab built and tested prototypes,
- the innovation manager evaluated the outcome of the process and

- an application for a patent on the new door mechanism was filed, and it was later approved.

4.5.4 Findings

The process suggested here is a combination of established methods to generate, evaluate and reduce a solution space in a Set-Based-inspired fashion. It focuses on the concept development phase of a PD process where design alternatives are generated and evaluated. A layout of the process is shown in Figure 13. The process begins with a creative synthesis in step 1 (see Figure 13), where an initial single functional requirement is the starting point. This case is unusual. It is more common to start with a design solution that satisfies the initial functional requirement. In step 2, the latter is decomposed into sub-functional requirements imposed by the design solutions generated from it. Creative synthesis is used to generate sub-solutions. Preferably several sub-solutions for each sub-function are created. The combinatorial solution space is modelled with a morphological matrix in step 4 and incompatible combinations are eliminated. In step 5, axiomatic coupling and complexity analysis are used to further reduce the solution space. Coupled design solutions are analysed using causal diagrammes and limit and trade-off curves in step 6. Strongly coupled designs are eliminated. The remaining coupled design solution and uncoupled solutions are passed on to evaluation in a Pugh matrix in step 7. If the process started with the first step of creative synthesis, there are likely more design solutions to analyse and evaluate. If so, the process from step 2 to step 7 is repeated. Remaining design solutions from each iteration of step 2 to step 7 (see Figure 13) are then finally evaluated in step 8, in which inferior solutions are eliminated.

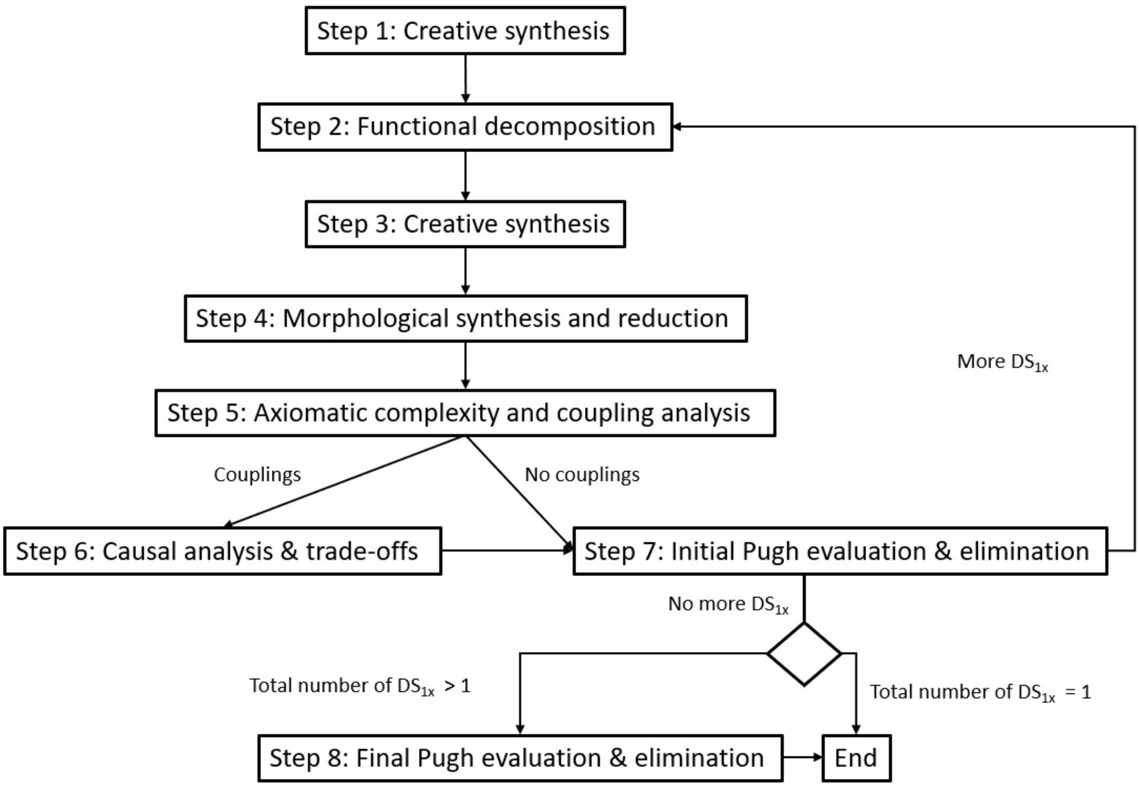


Figure 13. The described PD process.

The presented results show that the whole concept development process, including criteria specification, synthesis, evaluation, and reduction of a solution space, can be efficiently supported by established single methods when combined into one sufficient method super-set. With ISBD (Ström et al., 2016A; 2016B) as a framework, creative and systematic methods for synthesis can be used together with AD coupling and complexity analysis. Extended causal diagrammes can provide support for deepened internal dependency analysis and criteria balancing, and Pugh matrices can finally be used for relative evaluation and elimination.

To be possible to quickly introduce and apply, a process approach like the one described in paper E should have potential to produce valuable results already during the introduction phase, which paves the way for further use. This is achieved by:

- using well established methods that are at least partly known to the receiving organisation,
- applying the proposed process, with its involved methods, to real industrial design problems existing in the organisation,
- limiting the design problem to a system which is not too complex (maximum about 50 components),
- introducing it at team level in the organisation,
- applying the methodology in a workshop session with assistance from an outside expert and
- supporting the introduction with highly visual methods.

4.5.5 Conclusions

From the results presented in paper E it can be concluded that:

- it is feasible to combine and refine existing methods in a seamless concept development process,
- methods from systematic design and axiomatic design can be successfully combined with set-based design to synthesise, evaluate, and reduce a solution space of design alternatives and
- introduction of new working methods is facilitated if the methods can be applied to a design problem within the organization, and then return positive results, be tested at team level, and found feasible within a time frame of days.

4.6 Paper F - A set-based-inspired design process supported by axiomatic design and interactive evolutionary algorithms

This paper presents an approach towards a set-based-inspired concept development process for products with a solution space principally consisting of different solution alternatives and parameterised variants of these.

4.6.1 Introduction

The original description of Set-Based Design (SBD) does not say how to generate a solution space. There are furthermore no guidelines regarding which evaluation methods to use in relation to product specification contents and criteria characteristics. A difficulty, which is addressed in paper F, occurs when design solutions are governed by qualitative criteria, or when evaluation of the design in numerical terms cannot be carried out for some other reason. In these cases, human judgement is needed.

The hypothesis is that such a concept development process can be based on traditional synthesis methods, an SBD-inspired elimination strategy, Axiomatic Design, and Interactive Evolutionary Algorithms (IEAs) for synthesis as well as evaluation of solution candidates and successive reduction of the solution space.

4.6.2 Performed research

The approach in this research is inspired by the scientific work paradigm proposed by Jørgensen (1992). The process starts with case studies (Yin, 2009), where design problems are identified and studied in the left path in Figure 14. The analysis results in diagnoses that clarify problem issues such as needed activities and method support for different design tasks. In the next step, these are input to a synthesis of possible solution approaches. After evaluation, feasible approaches are conveyed to the right path in Figure 14 (see dashed arrow) to seek suitable theories and methods that might be used to solve the design problem. The theories and methods found are then, in a synthesis step, used to develop a process model with methods to be applied. The process model is finally applied on the design tasks in the case studies to judge its usefulness, reliability, validity, and generalizability in the analysis step in the right path in Figure 14.

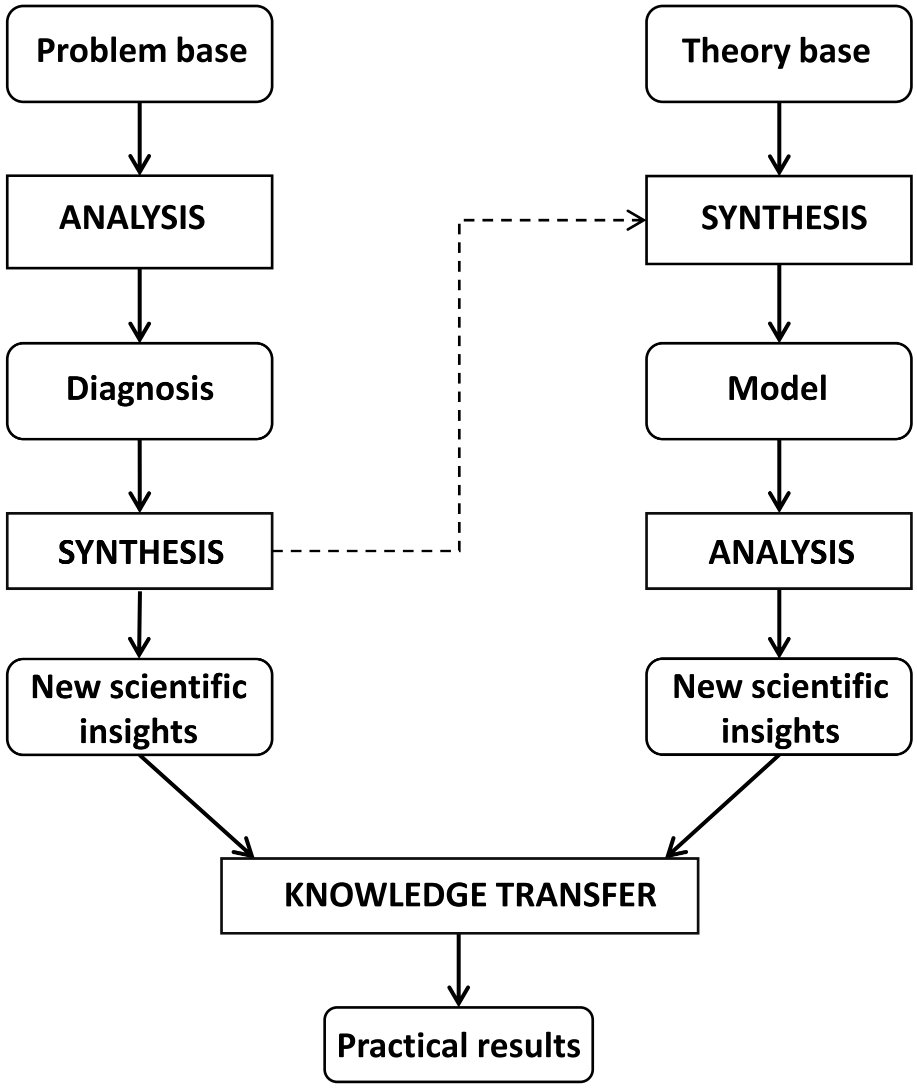


Figure 14. The scientific work paradigm proposed by Jørgensen (1992).

To assure validity, the presented research follows Jørgensen´s scientific work procedures (Jørgensen, 1992) with industrial case studies as well as theoretical studies. Each case is obtained from a different firm to assure industrial relevance. The design support that is created in the synthesis steps is tested on design problems by the firms supplying them. Results from the tests have been evaluated and validated by representatives of the firms. The firms were also visited by the researchers to experience the design problems in their natural environments. Notes and photos were taken during interviews as well as workshops. Industrial representatives were present when data from the design problems of each case was collected, and the results validated. The assumption has been that this way of working assures validity of the results.

In the case of the oil tube, the development engineers:

- specified the design task by supplying documents describing the application and examples of solutions,
- were interviewed by the researchers to get additional input to the requirements specification,
- commented on and evaluated solutions from competitors,

- participated in workshops (same as in paper F) to collect data and test the method,
- built and tested prototypes to verify that the final design fulfilled the requirements and
- evaluated the outcome of the process.

The development engineers who worked with the control knob:

- were interviewed by the researchers to get input to the requirements specification and to understand the design of the knob,
- specified the system for designing the control signal to the knob,
- built and provided a test rig for the control knob,
- participated in workshops to collect data and test the method and
- evaluated the outcome of the process.

4.6.3 Findings

The resulting model of a concept development process, showing how to ultimately arrive at a feasible solution, is illustrated in Figure 15.

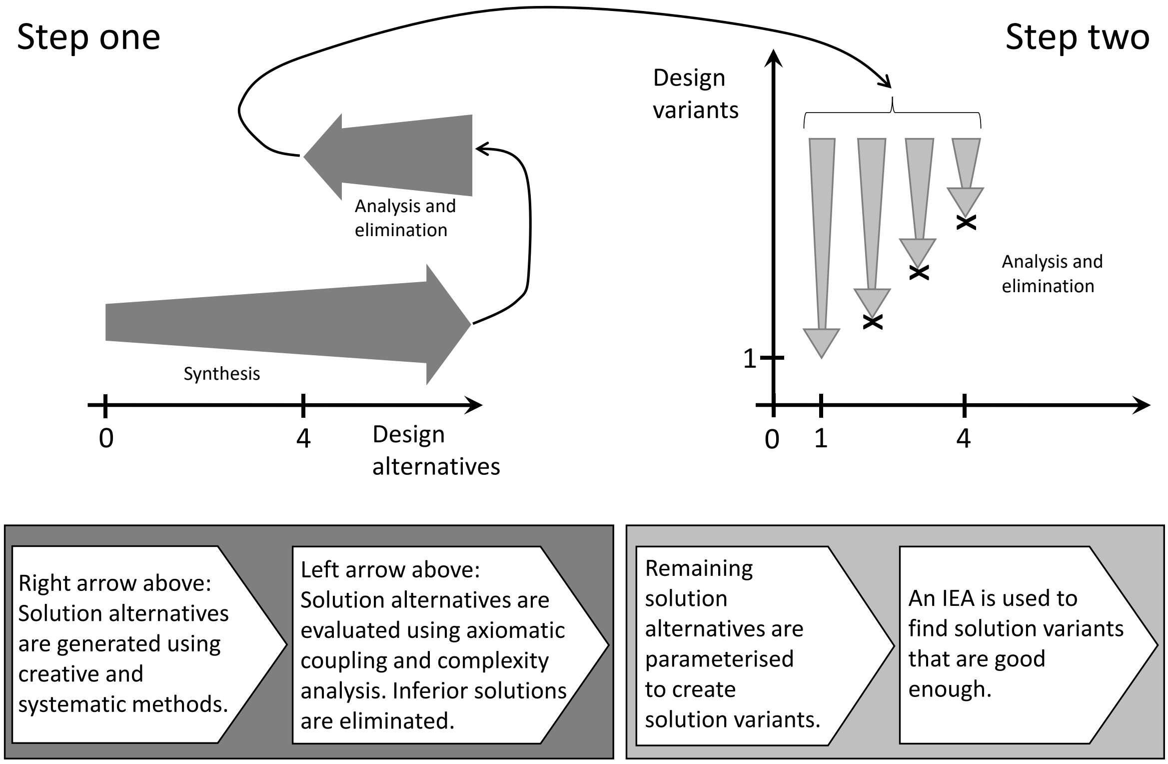


Figure 15. The two-step product development process.

Criteria are stated and analysed. The two-step process (see Figure 15) starts in step one with the use of classical creative or systematic synthesis methods to generate principally different design alternatives that fulfil the functional requirements. Solutions can be driven by both quantitative and qualitative functional requirements.

The axiomatic design theory (Suh, 1990) is then used to evaluate internal functional dependencies (couplings) and complexity (information content) of the alternatives. Following the AD axioms, strongly coupled and overly complex alternatives are eliminated.

In step two, the remaining alternatives are parameterised and investigated more thoroughly by varying design parameters. Solution variants, governed by different parameter settings, are regenerated using IEAs, and weak ones are eliminated. New solutions inherit features from the remaining solutions in the previous generation. New features also appear in some of the solutions and allow the user to test and compare them with the others. When doing this, development engineers with different expertise can join in ranking them and deciding which ones to discard after each iteration and identifying good enough specimens when, after some generations, they appear. As seen in the case studies, stakeholders outside the core design team can also be involved. The use of the IEAs helps the development engineers to test unexpected solutions and learn about the solution space. Feasible solutions are arrived at quicker than without IEAs.

4.6.4 Conclusions

The proposed new set-based-inspired process can handle a solution space of concept alternatives and parameterised variants of EM products. The knowledge contribution is that a combination of axiomatic design and interactive evolutionary algorithms can be used in a set-based-inspired framework to evaluate and reduce such a solution space with respect to quantitative as well as qualitative criteria.

For mature designs, like the tube example, development time can be reduced by 80%, whereas for less mature designs, like the control knob, the main result is that feasible concepts can be found in a shorter time frame.

It has been demonstrated how interactive evolutionary algorithms can handle nonquantifiable design parameters and, in combination with a set-based-inspired process, be used to improve designs. The proposed process further improved the involvement of secondary stakeholders, something that was much appreciated by the practitioners in the study.

5 Discussion

Based on the results in the appended papers, the research questions posed in the Introduction section are answered. Furthermore, aspects of validity, reliability and generalizability are discussed.

5.1 Answers to the research questions

The research questions are answered using results from one or several of the appended papers.

RQ1: What are the experiences from introducing LPD at tier 1 suppliers?

The experiences from introducing LPD at tier 1 suppliers are listed in Table 13.

Table 13. Findings related to RQ1.

No.	Findings
1	It is important to understand the principles of LPD.
2	It is an advantage to learn from others and stay updated on available information and knowledge.
3	Success in the introduction inspires the acceptance of LPD.
4	It is an advantage to have a lean enthusiast on site when introducing LPD.
5	It is important to have a reliable partner for education and training.
6	It is important to have a dedicated function to maintain the operational system.
7	It is favourable to have an LPD-aligned process model.
8	Stepwise introduction is favourable.
9	SPS and VP are relatively easy to make feasible.
10	Push from a dedicated function will need corresponding pull from the product realisation organisation.

Godbole et al. (2019) have done research on transformation to LPD. They explicitly point out findings 1, 7, 9 and 10 above, and implicitly finding number 5. They also point out knowledge management as problematic, and so does paper A. There are no contradictions between their results and the results of paper A. Included in paper A, but beyond their results, are the importance of listening to experience from others, as well as describing in more detail how people of the organisation can drive the transformation towards LPD. This indicates that RQ1 is well answered.

RQ2: How should the introduction of LPD be improved at tier 1 suppliers?

This can be answered by the findings presented in paper A, in which it is shown that the introduction of LPD is facilitated by the findings in Table 14.

Table 14. Findings related to RQ2.

No.	Findings
1	Supportive external information about LPD was received from LPD networks, seminars and newly published literature on the topic.
2	Implementation of lean production creates an interest to also introduce LPD.
3	Support from an internal lean enthusiast and from the management facilitates an LPD introduction.
4	A well-planned implementation route creates a pull in the organisation.
5	A function to maintain the implemented LPD system secures future use of it.

These five findings should be considered when introducing LPD at a tier 1 supplier.

These results resemble those of Godbole et al. (2019), who point out that the people of the organisation drive the transformation towards LPD (corresponding to findings three and five in Table 14), previous success with lean production will facilitate the introduction of LPD, and a well-planned implementation route is preferable. The importance of reading the same book describing LPD is emphasised by Godbole et al. (2019), which is included in the first finding in Table 14. They also describe a possible introduction route that is not included in the results of paper A, even though a well-planned implementation route is stated as important.

RQ3: How should a Set-Based-inspired design process be efficiently introduced in a development team within a reasonable time frame?

The proposed ISBD process should be introduced, at team level, by combining methods to generate, evaluate, and reduce a solution space of design alternatives to a not too complex design problem, as described in papers B and C.

The research question is well answered considering a reasonable time frame, which in this case is a couple of days. This is confirmed in eight studies described in papers B and C. The research does not cover a longer perspective. The introduction is, in the study, carried out at team level.

RQ4: How should existing methods and tools be combined to facilitate an efficient process for synthesis, evaluation, and reduction of a solution space of design alternatives?

Existing creative and systematic methods shall be combined in a seamless process to facilitate efficient synthesis, evaluation, and reduction of a solution space of design alternatives. The 6-3-5 method and alike can be used for creative synthesis. Suitable proposed systematic methods are EF-M decomposition, axiomatic coupling and complexity analysis, causal diagramme analysis, and Pugh matrix-based elimination. An initial problem description, based on FRs and Cs, shall be used as a starting point for synthesis of DS alternatives. A final solution is arrived at after elimination of inferior alternatives.

Paper E presents a consistent combination of existing and established methods in a logical sequence, each one applied as commonly used. The layout of the process described in paper E is of a linear fashion and works well this way. The presented ISBD approach is applied to EM products, and the answer to the research question only covers these types of products.

RQ5: How should a solution space of design variants be generated and evaluated in a Set-Based-inspired process when the solution space is limited by criteria which are qualitative or too complicated to be numerically defined?

A two-dimensional solution space, as in Figure 3, limited by criteria that are either qualitative or too complicated to be numerically defined, can be generated by first identifying FRs and Cs, governing the solution alternatives. These shall then be analysed with respect to functional couplings, complexity, and trade-offs as a base for elimination. The remaining feasible ones are then subject to parameterisation. A computer model including an IEA is a good way to vary parameters and use human judgement to eliminate inferior variants and use the remaining ones to generate new solutions in an iterative process.

The research question is answered by results that are verified on practical problems and found feasible by professionals. The results are assessed to be valid for the type of design alternatives treated in paper F, where design variants can be instantly generated in computer models, or in hardware models by parameter settings from an IEA.

In this work, the abovementioned methods were used to create a consistent development process. The methods used in each step may be replaced or complemented with other methods with similar purposes, e.g., brainstorming, functional analysis (Pahl, 2007), Kesselring matrices, and consideration of balance.

5.2 Reliability

To judge the reliability of the results, the following actions were taken. Data was collected and observations were made by more than one researcher, and the methods were adapted to the actual type of data. Well-established research methods and theories were used to secure reliability. The approach used was in each case confirmed by industrial representatives. Multiple sources of information were used whenever possible. In paper A, a descriptive framework and a rival framework were used to analyse the results.

5.3 Validity

To judge the validity of the results, the following actions were taken: The research was conducted by personnel from well-established research organisations with a policy to perform research that is purposive, inquisitive, informed, methodical, and communicable. These five conditions have been present in the described research and are in line with Cross (2007). Also, the use of well-established research methods such as case studies (Yin, 2009), DRM (Blessing and Chakrabarti, 2009) and SWP (Jørgensen, 1992) combined with well-established theories from the field of product development strengthen the validity.

Regarding paper A, results have been analysed in discussions in the research team, by comparisons with theoretical frameworks and rival frameworks, by comparing the state before and after the transformations to LPD and by comparing the two cases. The research team had a reference group associated with it, consisting of members from the participating firms and representatives of two OEMs and another supplier, all from the automotive industry. The reference group advised on the investigations and confirmed the validity of the results. The resemblance with the results of Godbole et al. (2019) strengthens the validity and shows that the results are relevant.

Furthermore, regarding papers B-F, validity was achieved by having experienced engineers from the participating firms suggest test cases and judge the results (Buur, 1990; Pedersen, 2000). For the studies in papers A, B, and C, explicit targets were set and fulfilled. Researchers and industrial representatives assessed the consistency of the developed methods and found it to be acceptable. Conformity between practical results and used theory further strengthens the validity. Also, the use of multiple cases that confirm the feasibility of the results contributes to the validity of the findings.

5.4 Generalisability

Generalisability is obtained using different and partly contrasting cases (Yin, 2009) regarding product types and firms. The results in papers B, C, and D were presented to the reference group associated with the study. The group members confirmed the usefulness of the results in a wider context. In conjunction with the work presented in paper F, one of the firms performed successful tests on other types of products than the ones in the test cases. The theories used in the developed methods in papers B-F are widely used and well described in many research publications. All these facts strengthen the generalisability of the results.

6 Conclusions

Introduction of LPD at a tier 1 supplier is facilitated by

- information about good examples,
- internal support by management,
- the existence of a lean enthusiast in the organization,
- an appropriate implementation plan,
- a function to maintain the LPD system and
- an understanding of the lean principles.

A combination of methods to generate, evaluate and reduce a solution space of design alternatives can be introduced in the time frame of one to two days if,

- it is applied to well-known, and not too complex, design problems,
- it is applied at team level in the form of a workshop event,
- it is facilitated by an expert on the methods used and
- the workshop is initiated by the team manager, who also participates in the event.

An efficient process for synthesis, evaluation, and reduction of a solution space of design alternatives can be created by combining the following existing methods:

- enhanced function-means modelling,
- morphological matrices for synthesis and elimination,
- axiomatic design to evaluate design alternatives,
- causal diagrammes to analyse design alternatives and
- Pugh matrices to evaluate and eliminate design alternatives

A solution space of design variants can be generated and evaluated in a set-based-inspired process with criteria that are either qualitative or too complicated to be numerically defined by using

- a defined set of functional and constraining requirements,
- axiomatic design to evaluate functional couplings and complexity,
- interactive evolutionary algorithms (IEAs) to generate and refine the variant solution space and
- a set-up of the IEA that does not overburden the user.

7 Future work

Below follows suggestions on future work that is divided into topics treated in the appended papers.

7.1 Next step regarding ISBD

ISBD as a one-to-two-day introduction process is proven successful in such a short time perspective. However, long-term studies have not been carried out to understand what impact it has on product development in a longer time perspective. It is possible that the proposed concept will need some type of adaption to be applied in large organisations. Further studies on how to repeat and permanent the methodology could be of interest.

ISBD was tested on mechanical design problems. However, many contemporary products are electromechanical, having electronic and sometimes software sub-systems. Research on design problems involving software, and the subdivision of systems into mechanical, electric, and digital could be interesting and an important extension of ISBD.

7.2 Further development of causal diagrammes

With today’s computers, it would be interesting to explore three-dimensional causal diagrammes by turning and rotating them on the screen to make it easier to study complex relations and corresponding trade-off and limit curves.

7.3 Combination of methods to support design of concept alternatives and variants of them

In line with the work in papers B-F, and the work of Gericke et al. (2020), it is likely that there are several more fruitful combinations of methods to explore in engineering design.

The process, as depicted in paper E, is sequential. The proposed sequence of methods might however not be optimal in product development projects in other industrial sectors than the one addressed in this research. This can possibly call for other work sequences, which could be the subject of future investigations.

The possibility to use AD and IEA for analysis, and explore a design space in a collaborative environment, can be further investigated. The assumption is that engineers in different functions can benefit from such possibilities prior to making important decisions, possibly integrated in a problem-solving loop.

7.4 Further use of IEAs

Another topic for further investigation is how to avoid user fatigue. One strategy is to reduce the information content in a population by elimination of clearly inferior solutions. If more than one solution remains, the next generation can be created using mutations and crossovers (Wahde, 2008).

The setup of a support system utilising an IEA can also be studied regarding the resources needed and how well the system suits different problem types.

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