Optimization-Based Configurators in the Product Development Process

Camilla Wehlin

Linköping Studies in Science and Technology
Licentiate Thesis No. 1914

Optimization-Based Configurators in the Product Development Process

Camilla Wehlin

Division of Product Realisation
Department of Management and Engineering
Linköping University, SE-581 83 Linköping, Sweden

Linköping, 2021

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

<https://creativecommons.org/licenses/by-nc/4.0/>

© Camilla Wehlin, 2021

Linköping Studies in Science and Technology
Licentiate Thesis No. 1914

ISBN 978-91-7929-611-7
ISSN 0280-7971

Distributed by:
Division of Product Realisation
Department of Management and Engineering
Linköping University
SE-581 83 Linköping, Sweden

All illustrations by Camilla Wehlin

Printed in Sweden by LiU-Tryck

PREFACE

The work presented in this Licentiate Thesis has been carried out at the Division of Product Realisation, Linköping University.

Thanks to everyone involved in the research projects, supervision and to the rest of the division. A special shout out to my office roomies, as well as the rest of my fellow PhD students at the division. Thanks also to my friends and family, including my four-pawed favorite Sally, who in addition has done a great job as a stand-in co-worker during the last year of home office *pandemic edition*.

ABSTRACT

Requirements from the market on customer responsiveness and pressure on the environmental profiles of companies, both internally and externally, are challenging companies to amend their processes in all possible aspects in order to stay competitive. For product development companies, the challenges often lie in developing and delivering products rapidly, customized and meeting the set requirements. For highly customized products, mass customization is a term describing a company setting in which products meet each customer's individual requirements but are still produced and delivered at near mass-production efficiency. The concept of mass customization is becoming a prerequisite for the survival of companies within this niche. For more complex engineering products, the complexity increases as new technology is introduced, which needs to be integrated to increase the product's performance at a rapid pace. Also for complex products, the level of customization is increasing, which motivates the support of tools enabling an increase in customization.

In both mass customized and complex products, the obstacles to overcome are the repetitive resource inefficient work, knowledge capture and reuse, uncoordinated processes, and a high number of iterations between departments within the company. This often boils down to the well-established so-called design paradox describing the lack of knowledge about a product and process in the early stages of design, where the design freedom is still high. As knowledge increases throughout the process, the design freedom in contrast shrinks, and the costs of changes increase exponentially. Design automation, design optimization and the use of configurators are all methods used to reduce repetitive work, increase and capture knowledge, and integrate the product development process.

This thesis presents how configurators based on optimization can be used and integrated into the product development process of engineering intensive configurable products and components, such as engineer-to-order (ETO) products. Design automation and design optimization have been identified as key building blocks to extend the use of configurators. This has been done in two different application cases within two different research projects, to evaluate how these configurator systems may be modeled and utilized. The first application case concerns the automation of hose routing in vehicles and the second application case concerns spiral staircases intended for mass customization.

APPENDED PAPERS

The four papers listed below are the foundation of this licentiate thesis, and are appended in the end of the thesis. They will be referred to as Paper A-D in the text.

PAPER A

Wehlin, C., Persson, J. A. and Ölvander, J. (2020) *Multi-Objective Optimization of Hose Assembly Routing for Vehicles*, in Proceedings of the Design Society: DESIGN Conference, pp. 471–480. (Awarded with ‘Reviewers’ Favorite’)

PAPER B

Poot, L. P., Wehlin, C., Ölvander, J. and Tarkian, M. (2020) *Integrating Sales and Design: Applying CAD Configurators in the Product Development Process*, in Proceedings of the Design Society: DESIGN Conference. Cambridge University Press, pp. 345–354.

PAPER C

Vidner, O., Wehlin, C., Persson, J. A. and Ölvander, J. (2021) *Configuring Customized Products with Design Optimization and Value Driven Design*, in Proceedings of the Design Society: 23rd International Conference on Engineering Design, ICED21. (accepted)

PAPER D

Wehlin, C., Vidner, O., Poot, L. P. and Tarkian, M. (2021) *Integrating Sales, Design and Production: A Configuration System for Automation in Mass Customization*, in 47th Design Automation Conference (DAC). ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference: American Society of Mechanical Engineers (accepted)

CONTENTS

1. INTRODUCTION	1
1.1. Aim.....	3
1.2. Approach	4
1.3. The Design Research Methodology	5
1.4. Outline of the Thesis.....	6
2. FRAME OF REFERENCE	7
2.1. Design Automation	7
2.2. Product Customization.....	9
2.3. Optimization in Engineering Design	14
3. APPLICATION CASES	19
3.1. Automation of Hose Routing in Vehicles	19
3.2. Mass Customized Spiral Staircases.....	23
4. DISCUSSION	29
4.1. Limitations	29
4.2. Optimization in Configurators to Achieve Automation.....	30
4.3. Effects on the Product Development Process	33
5. CONCLUSIONS	35
5.1. Answering the Research Questions	35
5.2. Future Work	37
6. REFERENCES	39

INTRODUCTION

Industry is facing ever-growing demands from the market to increase customization and to launch new products at an accelerating pace. Doing so means that a company's assets need to be carefully utilized, without any room for costly errors. The use of resources is not only an economic factor, but from a broader perspective it also plays an indisputable role in environmental aspects – an issue that will keep increasing as long as the temperature of the planet also does so. Using resources in a sophisticated way, in terms of both time and knowledge, is a factor of survival against competitors. Companies need to continuously optimize their processes, offer products with increased customization, and integrate new technologies into the development of those products. Achieving this demands effort in several areas, one of which is in product development processes.

The, more or less, holy grail of product development is the so-called design paradox; or rather the endeavor to overcome it. As depicted in Figure 1, this paradox lies in the fact that, as knowledge about the product being developed increases with time, the costs of making changes in the design increase as well (Ullman, 2009). Thus, the aim often boils down to increasing knowledge earlier on in the process when there is still room for change, in order to generate a greater chance of delivering a successful product in an efficient way.

This knowledge needs to be either created or retrieved, i.e. reused knowledge. Knowledge in this context has a wide scope throughout the different stages of

Figure 1 *The design paradox, adapted from Verhagen et al. (2012).*

the product development process; from a thorough understanding of customer needs in the initial stage, to knowledge of detailed product properties in the development stages and manufacturing knowledge in the production stage. One way of creating knowledge is to use computational methods to evaluate the design space, where design optimization is one of these. Knowledge reuse can be achieved by the use of knowledge-based engineering (KBE) (La Rocca, 2012), which in an applied form can be used in design automation systems, aimed at reducing repetitive and tedious work in the design process. One such system that is widely used for customized products is configurator systems (Hvam, Mortensen and Riis, 2008), which aids the configuration process by taking input and requirements and translating them into variants of a product suitable to each specific case. Configurator systems traditionally use pre-defined knowledge, defined as rules applied to pre-set modules of the product, configured in a sequential way. Products configured in this way are referred to as configure-to-order (CTO) products, which can be assembled and delivered rapidly because many of the engineering activities are completed prior to the customers entering the process. The CTO approach implies that the number of possible solutions for configurations is limited, and thus so is the use of this kind of configurator. Engineer-to-order (ETO) products, on the other hand, as the name implies, are engineered for each order and may therefore be more successful in meeting the customization demands of the market. However, they traditionally require more resources, which is reflected in the costs and delivery times of these products.

In other product development processes for less highly customized products,

such as cars, there are engineering-intensive activities that resemble the elements of ETO in that they are repetitive and configurable in the sense that the same problem definition occurs in continuous development projects with changing prerequisites (similar to the changing prerequisites from customer to customer in a sales context).

In this thesis, the rationale is that design optimization, together with KBE, can be used to enable automation and configuring of engineering-intensive configurable products and components where the design space is dynamic, unpredictable and/or not well defined. Extending the use of configurators using this approach can be a way to meet market demands by enabling a higher level of customization, adapting to new technology integration in products and employing a more resource-efficient development process.

1.1. AIM

In this work, configuration systems based on reusable and flexible optimization formulations in different industrial contexts have been developed and evaluated. The aim is thus to contribute with implemented demonstrations of how these systems can be used to reduce the resources needed to develop and deliver a product that meets the customer's demands for customization and is a success factor for companies. The aim is also to contribute to the knowledge and understanding of the possibilities and challenges within this area. The approach of the research conducted has thus been of an exploratory nature. The aim is boiled down to the following research questions, which are addressed within this thesis:

RQ1: Why is the utilization of optimization in configurators suitable for achieving automation for engineering-intensive configurable products?

RQ2: How would the utilization of optimization in configurators affect the product development process for engineering-intensive configurable products?

RQ1 covers the technical aspects of the configurator systems developed within the frame of this thesis, and is derived from the evaluation of the development and results achieved with those configuration systems. RQ2

aims to condense the implications of the use of these configurator systems at a higher level of abstraction of the product development process. Both research questions are formulated in a relatively open-ended way, for the sake of this thesis' exploratory approach to investigating the opportunities to expand the use of configurators for engineering-intensive configurable products.

1.2. APPROACH

The work conducted within this thesis has been undertaken within the frames of two separate research projects: AutoPack^a and e-FACTORY^b. In both projects, the objectives and approaches are similar in that they both aim to rationalize the engineering and product development process by developing design automation and optimization tools and methods. The application products and their development processes, however, differ between the projects. In AutoPack, the aim is to develop tools to aid the product development process for complex products with integrated systems. There, hose routing in the engine compartments of vehicles has been identified as a tedious task in the development process, involving many iterations and much repetitive work in order to satisfy the constraints and objectives from the multiple disciplines and departments involved. In e-FACTORY, the focus is on companies developing and producing highly customized products, with the aim of rationalizing the entire process, from sales to delivery. The primary application case, around which the methods and tools have been developed within this project, is spiral staircases.

The research conducted has taken an exploratory approach, investigating and developing tools for these differing applications using similar technologies. What is common to both cases is that, in their current state, the application case products require a large amount of engineering resources for each new configuration of the product.

In its over-arching perspective, the work conducted within this thesis and the activities in the two research projects have followed the Design Research

a. AutoPack (DNR 2017-03065) is a project funded by Sweden's innovation agency Vinnova through the partnership program Strategic Vehicle Research and Innovation (FFI).

b. e-FACTORY (DNR 2018-01584) is a project funded by Produktion2030 – a strategic innovation program supported by Vinnova, the Swedish Energy Agency, and Formas.

Methodology (DRM), as suggested by Blessing and Chakrabarti (2009). This is described further in the following subsection. Close collaboration with the research projects' industrial partners have tilted the work towards the integration and application of the developed product configuration systems from a holistic point of view.

1.3. THE DESIGN RESEARCH METHODOLOGY

The Design Research Methodology (DRM) was developed to cover two important aspects of design research: the understanding of phenomena in design and the development of methods. Additionally, the method was developed for the purpose of dealing with the multiple disciplines involved in engineering design, such as engineering science, cognitive science and computer science, which also results in interconnectivities that need to be addressed. The DRM consists of four stages, which are usually performed in iterations between them rather than sequentially. The stages are described briefly below:

- Criteria: Specification of measurable criteria to judge success and indications of validity of the research.
- Descriptive Study I (DS-I): Identification of the factors for success and the interaction between them, through observations and literature reviews.
- Prescriptive Study (PS): Development of design guidelines, methods and tools and generation of a scenario for the desired situation.
- Descriptive Study II (DS-II): Evaluation of the design guidelines, methods and tools developed in the previous stage.

For this thesis project, the focus has been mainly on the DS-I and PS stages of the methodology. The conducted studies are presented in the appended papers A–D. Paper A presents the work conducted within the AutoPack project concerning automated hose routing for vehicles. This work can be seen as the first iteration of a criteria, descriptive (DS-I) and prescriptive (PS) study – work that continued iterating (within the AutoPack project) beyond the scope of this thesis project, see (Gustafsson, Persson and Tarkian, 2021). Hence, paper A consists of a literature review of the field, as well as interviews and workshops with engineers to define the goals of the project and identify the current state-

Figure 2 *The work conducted and presented in the appended papers in relation to the DRM.*

of-practice. Thereafter, new design methods and tools were developed and tested in a laboratory setting. Papers B and C presents the work conducted in the first iteration criteria, descriptive (DS-I) and prescriptive (PS) study of the e-FACTORY project, using a similar approach as that outlined for paper A. Paper D presents a second iteration of the methods and tools developed in Papers B and C. An overview of the papers in correlation to the research projects and stages of the DRM is presented in Figure 2.

1.4. OUTLINE OF THE THESIS

This thesis is structured as follows. In Chapter 2, the frame of reference is presented, covering the areas of design automation, design optimization and product customization. In Chapter 3, the application cases of the two research projects of the thesis are presented. This includes an introduction to the application cases studied and a summary of the work presented in the appended papers. This is followed by a discussion of the work in Chapter 4. Lastly, in Chapter 5, the conclusions of the thesis, including answers to the research questions, are presented.

FRAME OF REFERENCE

The theory that the work in this thesis builds upon, and aims to contribute to, is mainly design automation and design optimization for increased customization of products. Design automation and optimization are broad areas of research aiming to develop methods and tools that can aid the product development process. In a nutshell, with better tools and methods in the development process, better products can be developed using fewer resources. *Better* here refers to performance, quality, customization and/or sustainability. Within this thesis, this means developing tools and methods to enable more efficient product development for configurable engineering-intensive products by means of design automation and design optimization.

2.1. DESIGN AUTOMATION

As in many fields of science and research, as well as the wider society, automation is being sought in order to reduce human intervention in different activities, as a way to reduce the resources consumed and errors made, and often also to improve the quality of a task. In engineering design, many activities are of a repetitive and tedious nature, and thus also a source of errors. Hence, design activities are subjects for automation and can be a means of remaining competitive by shortening lead times (Cederfeldt and Elgh, 2005). For design

automation, CAD tools have developed into what Tomiyama (2007) describes as intelligent CAD systems, which in its original use was developed for routine tasks and re-design rather than creating new products. CAD as a technology falls within the umbrella term computer aided technologies (CAx), which include, for example (computer aided) manufacturing (CAM) or (computer aided) engineering (CAE), which are continuously advancing the state-of-the-art of design automation.

Design automation may refer to solely geometrical CAD tasks, where parametric CAD is a fundamental enabler. An applied example is the use of high-level CAD templates (HLCt), where the product knowledge is stored in the templates themselves (Amadori et al., 2012). Using HLCt allows for topological changes (instantiations), which can be seen as a higher level of automation than parametric CAD, which only enables morphological changes. Design automation may also involve other CAx areas in other disciplines. An example of CAM-oriented applications includes manufacturability analysis, as developed by Johansson (2011). The development of multidisciplinary design automation systems for concurrent use is a future opportunity and is needed for advancing the field and support, for example increased and efficient customization (Heikkinen, 2021).

2.1.1. KNOWLEDGE BASED ENGINEERING

Throughout the process of design, production, as well as the entire lifecycle of products, an immense amount of knowledge is generated, processed and applied. Knowledge based engineering (KBE) deals with this area, for example by integration with different CAx applications and knowledge management. La Rocca (2012) defines KBE as a technology to capture and systematically reuse product and process engineering knowledge with the aim of reducing time and cost resources of product development, where one central enabler is the automation of repetitive and non-creative tasks. KBE has also been described as an engineering method that benefits design automation systems for customization by the merging of object-oriented programming, artificial intelligence and CAD (Chapman and Pinfold, 2001). Opportunities for successful implementation of KBE have been pointed out to lie in the early stages of the product development process, with reference to the design paradox, where KBE can contribute with crucial knowledge (Verhagen et al., 2012).

The fundamental aim and definition of KBE overlap with those of design automation: to automate repetitive tasks, reuse knowledge and eliminate

errors. Design automation can be achieved and implemented effectively with the development of knowledge-based systems (KBSs) (Tarkian, 2012).

A KBS is an applied use of KBE, typically consisting of two main modules: a knowledge-base and an inference engine. The knowledge-base is the repository for the domain-specific information stored as rules or facts (La Rocca, 2012), which may be sequential and contain complex interrelations (Hopgood, 2001). The interpretation, selection and application of the rules and information inside the knowledge-base is managed by the inference engine (Hopgood, 2001). Thus, the inference engine can be seen as the reasoning mechanism of the KBS, similar to a human expert deriving answers to given problems (La Rocca, 2012). The performance of the system is hence tied to the inference engine. Separating these two modules of the system means that the performance of the system is not affected by continuous updates of the content in the knowledge-base, which is needed in order to have a well-functioning and well-maintained design automation framework (Tarkian, 2012). Lack of maintenance of the knowledge-base in product configurator systems, further described in section 2.2.3, has been pointed out as a failure mode causing the return on investment of the system to be negative (Shafiee, Hvam and Haug, 2019).

2.2. PRODUCT CUSTOMIZATION

Customization as a concept is not a novel idea. But the premises on which customization is achieved and realized have evolved over time. The era of mass production paved the way for offerings of a wider range of products to a wider range of customers and markets, as a result of the lower production costs that mass production entails. The drawback to this approach is that the customization element is not present, which is a demand that is increasing and becoming a market advantage. Also, certain products ultimately need customization and cannot be produced under mass production circumstances.

2.2.1. MASS CUSTOMIZATION

Mass customization has become a target ideal for companies to be successful and meet ever-increasing customer demands. It can be seen as the paradigm that is succeeding the era of mass production. In mass customization, the degree of customization is increased without a corresponding decrease in delivery time or costs (Tseng, Jiao and Merchant, 1996). This means overcoming

the trade-off between mass production and customization. It implies a process in which customers are highly integrated, together with flexible and responsive processes and production lines (Piller, 2004). The active customer integration implied by mass customization is needed in order to gain crucial input affecting the design, production and delivery of the product (Wang and Tseng, 2009). Advancements in the field of mass customization have been made over the last few decades through the development of manufacturing technologies, as well as tools and methods for integrating customers into the process (Fogliatto, da Silveira and Borenstein, 2012). It has also been pointed out as an important competitive advantage (Salvador, Martin de Holan and Piller, 2009).

Achieving mass customization ultimately implies a multi-disciplinary effort due to the multi-dimensional problems that need to be solved. It needs solutions in the following three refinement states of a mass customized product:

- Customer requirements: tools to integrate the customer into the process, in order to capture their needs and requirements.
- Product design: The actual product with the customized design.
- Production: Flexibility in production lines, with production technology enabling the required manufacturing flexibility.

Each area reveals its own individual issues, as well as approaches to overcome them. On the front-end, for the tools to integrate customers into the process, issues have been raised concerning factors such as the perceived complexity of the product and its choices and user interaction with IT tools (Franke and Piller, 2003). For the product design, a common approach is to standardize and modularize the components of the product, with a finite number of solutions as a prerequisite for achieving mass customization (Piller, 2004). This approach of product family design falls within the definition of platform products. Definitions of platform products vary among contexts, but an artefact-focused definition is that formulated by Meyer and Lehnerd (1997), stating that platform products are a set of common components, modules or parts from which a stream of derivative products can be efficiently developed and launched. The product platform approach has been an important and successful tool for achieving mass customization (Huang, Simpson and Pine II, 2005).

In the production of the products, manufacturing technologies are being developed and employed in favor of mass customization, e.g. additive manufacturing (AM, commonly known as 3D-printing) and computer numerical

control (CNC) machining tools, as well as software to utilize them. But apart from these three refinement states of a mass customized product, solutions are also needed to be able to glue the stages together, enabling efficient sequencing from one stage to the other, i.e.:

- Methods and tools to define a product to fit the customer's needs (translation of customer requirements to a specific product design)
- Methods and tools to set up and adapt the production of each product (translating the product design to a specific production setup)

This is illustrated in Figure 3. The use of product configurators is a common approach for the first one, whereas the latter may involve computer-aided manufacturing (CAM) and other automation approaches to generate production preparation data.

Figure 3 Building blocks in achieving mass customization.

2.2.2. CUSTOMER ORDER DECOUPLING POINTS

One way to describe a kind of manufacturing setup is by means of a particular customer order decoupling point (CODP). The CODP depicts the decoupling between uncertain and certain decision-making for manufacturers regarding product detail specifications demand and quantity, as well as when and where to deliver them (Rudberg and Wikner, 2004). The commonly described four types of CODPs, illustrated in Figure 4, are:

- Engineer-to-order (ETO): decisions regarding product design and delivery are made and developed after the order has been placed, with high customer participation and thus the highest level of customization (of the four types of CODPs).

- Make-to-order/manufacture-to-order (MTO): customization level is delimited compared to ETO products, with parts of the order being customized while others are not and are manufactured as the order is placed.
- Configure-to-order (CTO), sometimes denoted as assemble-to-order (ATO): Pre-defined configuration alternatives of products are often already manufactured at the time of the order, and thus can be quickly assembled and delivered.
- Make-to-stock/manufacture-to-stock (MTS): No customization for individual orders is possible in the MTS set-up, where the manufacturing of products depends on predictions of customer demand.

Figure 4 CODP's, adapted from Rudberg and Wikner (2004).

As seen in the list of CODPs, the level of customization is descending from ETO to MTS, but costs are also decreasing from ETO down to MTS. The risks and disadvantages of having a setup closer to ETO are that a lot of resources are needed for each order and that it depends on a full understanding of the customer's needs and requirements. Misinterpretations of those increases the resources needed for each order even further. On the other hand, the risks and disadvantages with a setup in the CTO to MTS range are that predictions of demand are faulty, and hence the manufacturer is not able to satisfy certain customer segments.

The CODP can be used as a tool for understanding and achieving mass customization, especially when seeing it from customization perspectives in both engineering and production (Rudberg and Wikner, 2004), which may

differ in their capabilities. One strategy can be to transform a product catalogue from ETO to CTO. But, as the customization possible may decrease when moving from ETO to CTO, the production stage is targeted as a strategy to push ETO towards mass customization, e.g. the automation of production lines, as in Sjøbakk, Thomassen and Alfnes (2014). Besides limitations in the degree of customization that CTO products may imply, the foundation of CTO products is that the standardized configurations and their solution spaces need to be well defined.

2.2.3. PRODUCT CONFIGURATION SYSTEMS

A rationalized definition like that suggested by Forza and Salvador (2002) is that a product configurator is used for both sales and engineering support, to identify and capture commercial characteristics from a customer, then translate these into technical characteristics of the product to be manufactured. A requirement for a configurable product is consequently the ability to link its commercial characteristics to its technical ones (Forza and Salvador, 2008). Furthermore, a product configurator ensures feasibility of a product design and feeds back information relevant to the users of the system and is thus often used in a sales context to support the sales process.

A product configurator is commonly mentioned in the literature in terms of product configuration systems (PCS). A PCS is defined as an IT system supporting the sales, product design and development of manufacturing specifications for customized products (Hvam, Mortensen and Riis, 2008). PCSs have been pointed out as central enablers for companies to achieve mass customization (Hvam, Mortensen and Riis, 2008). The customer involvement and input that is central to mass customization often occurs at the sales (or quotation) stage – a critical activity for the rest of the process. The ability to generate quotations giving accurate cost and delivery estimations at the sales stage is necessary for remaining competitive in mass customization settings (Elgh, 2012). With a PCS, quotations and product and production specifications can be made more accurately and in an efficient way, avoiding errors in the process (Hvam, Mortensen and Riis, 2008). The reduction in the resources required for specification making using a PCS have been measured as up to 95 % (Haug, Hvam and Mortensen, 2011). This reduction in resources is an effect of the PCS ensuring the feasibility of the solutions built on relevant data (Myrodia, Kristjansdottir and Hvam, 2017). This means that the knowledge-base of the PCS needs to be maintained, otherwise risking to lose its profitability

(Shafiee, Hvam and Haug, 2019). Maintaining the PCS also contributes to the formalization and availability of knowledge across departments within a company, reducing the risk of competence becoming locked to key employees (Forza and Salvador, 2002).

2.3. OPTIMIZATION IN ENGINEERING DESIGN

Design automation, KBE and PCSs can be seen as tools that are employed to realize a product or component given certain input values. Having established a well-functioning product model using these tools to automate the design given certain inputs enables the use of optimization algorithms to investigate what input values should be used to achieve the optimal characteristics of the design. Here, the design can be a product, a component of a product or a system of products. This method is referred to as design optimization. The main elements of design optimization, as described by Persson and Ölvander (2019), are:

- Design variables: changeable input values to the design, for example a length or quantity in the design, that can be determined by performing an optimization.
- Parameters: other input values affecting the design and the optimization of it, but which cannot be changed by the designer, for example gravitational force.
- Objectives: desired goal characteristics of a design formulated as mathematical functions, for example minimizing costs or maximizing performance.
- Constraints: characteristics of a design that need to be limited to below, above or equal to a set value, for example maximum allowed stress in a component.

Design optimization is primarily used during the detailed design stages to define specific design variables. However, it could also be used during the early phases of the design process, for exploring and evaluating the design space and increasing knowledge about the product. Using different CAX disciplines in design optimization means that investigation can become even more thorough, thus generating more valuable knowledge. Design automation is

thus an enabler for advancing the optimization in such ways, to generate and regenerate for example a CAD model with different design variable values to evaluate objectives in an optimization run. In terms of a KBS, the inference engine can be built on, or connected to, an optimization model. In this manner, design automation as a concept can, with design optimization, be interpreted as meaning that (parts of) the design process itself is (are) the subject of automation, not only the design tasks within it.

Engineering problems usually deal with multiple objectives, such as material costs and product performance, which then classifies them as multi-objective optimization (MOO) problems. In these cases, engineers are faced with the task of making design decisions regarding the relative importance of the objectives (Sobieszcanski-Sobieski, Morris and van Tooren, 2015), since the multiple objectives often are conflicting. This can be made either pre- or post-optimization, formulated as a weighted sum (then regarded as a single-objective optimization problem) or selecting designs on the so-called Pareto frontier. For customized products, the relative importance of the objectives, as well as the design variables' and constraints' upper and lower limits, can be determined by customer-specific requirements on a case-by-case basis.

To solve a design optimization problem and perform an optimization, a broad range of optimization algorithms have been developed. One branch among these is evolutionary algorithms. The fundamental ideas behind these algorithms stem from behaviors and processes present in nature. Genetic algorithms (GAs) are a category of evolutionary algorithms that are built on the advancement of fit individuals, as representations of solutions to real-world problems, evolving throughout generations similarly to biological organisms (Goldberg, 1989). The range of problems successfully solved using GAs is wide (Beasley, Bull and Martin, 1993). Due to this advantage, GAs have gained popularity in design optimization, and have been successfully used to solve a wide range of engineering problems involving a mixture of real and discrete variables (Andersson, 2000). Although other algorithms are likely to outperform GAs in terms of efficiency in finding global optima to specific problems, their strength lies in the range of problems where they will find acceptably good solutions acceptably quickly, as formulated by Beasley, Bull and Martin (1993).

The computational efficiency of a design optimization problem is crucial as it is a matter of time and cost, especially in industrial uses (Giesling and Barthelemy, 1998). Depending on the context, it may be the determining factor

for being used at all. Including CAx methods with computationally heavy analyses, such as finite element method (FEM) analysis, in the evaluation of a design in the optimization results in a computationally expensive task when accounting for the many evaluations that take place during an optimization run. Apart from that, the design automation model used to perform the analysis may also be computationally heavy to regenerate for each evaluation.

2.3.1. ENTERPRISE-WIDE OPTIMIZATION

As production processes expand, sites become geographically distributed and concurrent development and sales processes increase, tools to manage and optimize the asset use and distribution throughout the entire supply chain are needed. These issues are addressed within the field of enterprise-wide optimization (EWO), originating from the processing industry (Grossmann, 2005). The definition of this term is now rather industry generic and independent of the type of context. It is that EWO concerns the coordinated optimization of the operations of the full supply chain with the objectives of increasing asset utilization, maximizing profit, managing inventory levels and decreasing environmental impact (Gounaris and Grossmann, 2019). Both the challenges and solutions associated with EWO of process industries are similar to those in product development in general, and mass customization in particular. These are the integration and coordination of information to achieve coordinated decision-making across a widely distributed (both geographically and functionally) company organization. This is achieved with modern IT tools utilizing, for example, MOO (Gounaris and Grossmann, 2019). CAE software developers have addressed EWO as having the potential to extend and advance the use of multidisciplinary design optimization systems.^a

Applying an EWO strategy to mass customization would mean that the customization of a product is not just seen as an activity isolated to a specific customer, but rather that there is an active coordination among the resources of the full supply chain of the company, including concurrent customization sales cases.

2.3.2. OPTIMIZATION FOR CUSTOMIZATION

Optimization can be used in various ways in the effort to increase the customization of products. One of these ways is determining the variable

a. <https://www.esteco.com/blog/towards-enterprise-wide-optimization>

settings of a product platform, where multi-objective optimization helps to maximize the commonalities among the products in order to minimize production costs and the trade-off for the most profitable product family in production cost versus product performance (Simpson, 2004). There, the optimization is conducted during the development of the product family, to be offered later as a CTO product. But optimization can also be used actively in each sales context in a product configurator. As an example, Usma-Alvarez, Fuss and Subic (2014) used design optimization to configure rugby wheelchairs to specific customer anthropometrics and performance requirements. Klushin, Fortin and Tekic (2018) presented a framework for the optimization of size-adjustable parts applied to vending machines, which were explicitly stated to be aimed for mass customization. Thus, optimization can be regarded as an enabler for mass customization and the extended use of configurators.

APPLICATION CASES

This chapter contains a summary of the work conducted within the scope of this thesis. The work has generated a set of four papers, which are appended to the thesis, in which a more thorough description of the application cases, the tools and methods developed, and their results are presented. As briefly introduced in Chapter 1, the work conducted within this thesis has been carried out within the frames of two separate research projects, which provided one application case each. These are the automation of hose routing in vehicles and mass customized spiral staircases.

3.1. AUTOMATION OF HOSE ROUTING IN VEHICLES

The AutoPack research project is aimed to automate processes in the resource-demanding activity of designing the routing of hoses in the engine compartments of vehicles. As the complexity of vehicles increases with the integration of systems and the introduction of new technologies, the hose routing task also becomes more complex. One of the collaborating partners in the project has estimated that the activity allocates 40,000 hours of engineering work at a cost of 25 MSEK annually in their development of cars. The following is a summary of the work presented in Paper A.

3.1.1. CASE BACKGROUND

In the process of routing hoses in vehicles, many requirements from different disciplines need to be met. It involves engineering activity from different departments, which leads to many iterations in the process. An important aspect to consider in the process is the dynamic clearance needed in order to avoid contact between the hoses and their surroundings when the vehicle and the engine generate movement and vibrations. In addition to that, other aspects include technical performance, production and assembly aspects, and overall costs. Moreover, the physical space through which the hoses are routed are confined and limited. Different models of cars, subsequent generations of a particular model, or even different configurations of the same model, render different prerequisites for the hose configuration process due to the differing geometries of the hoses, their surroundings, the number of hoses, and so on. In other words, the design space changes for each configuration case. All in all, the process is complex and in need of a higher degree of automation.

The tools available and currently in use (at the collaborating car manufacturer) for the hose routing are supporting the optimization of single hoses and is used to simulate the dynamic characteristics of a complete assembly of hoses. But there is a need for a holistic solution to the design of an assembly of multiple hoses within the same geometrical space, in order to decrease the number of iterations and resources needed in the process.

3.1.2. DESCRIPTION OF THE FRAMEWORK

In Paper A, a proposed method for automated hose routing assemblies in vehicles is presented. This can provide a conceptual solution for the assembly, taking several disciplines into account simultaneously. The method includes a developed design automation and optimization framework. Referring to a generic product development process, such as the one suggested by Ulrich and Eppinger (2012), the method has been developed for the system-level design stage, to generate a hose routing assembly that will initiate the following detailed design stage of the process.

The framework consists of four main parts: CAD, an interface, simulation and optimization, as illustrated in Figure 5. First, points representing the start and end nodes of each hose are set out in the surrounding geometry in a CAD environment, representing different engine compartments and hose requirements. An interface is used to import the CAD data and to enter routing prerequisites such as hose cross-sectional diameters. An automated routing

Figure 5 *The framework for the automated hose routing.*

is then initiated from the interface, based on the given inputs. A simulation software finds collision-free paths for each hose, with respect to the surrounding geometry. The hose assembly is then simulated with gravitation and stress. The routing results are obtained from the simulation and are evaluated as optimization objectives. The routing input is controlled by an optimization algorithm, meaning that it regulates the order in which the hoses are routed, and through which points they are drawn. The result of an optimization run is a set of Pareto-optimal hose assembly designs.

The objectives in the optimization formulation are to minimize the total volume of the hoses in the assembly, to minimize the highest stress of any of the hoses, to maximize the clearance in between hoses and between the hoses and specified critical components. Clearance is necessary to account for vibrations, especially near components with sharp edges or hot surfaces (in need for additional monitoring.) Designs where collision-free paths for all hoses in the assembly are not found are considered unfeasible. The design variables are the permutation deciding the order in which the hoses are routed and the placement of so called via-points. Via-points are used to control the shape of the hose. Varying the placement of them enables the optimization algorithm to find routing compromises in order to obtain globally optimized assemblies. The complete problem formulation is found in Paper A.

3.1.3. RESULT

The method was implemented using CATIA V5 to set up the CAD environment, Excel as interface and bridging of the modules of the framework, IPS (Fraunhofer Chalmers Center, 2021) for simulations and routing controlled

with a Lua script (Huang, Simpson and Pine II, 2005) and ModeFRONTIER as the optimization engine.

The Lua script is created using information from the Excel sheet, which contains setup values for the hoses that are to be routed, coordinates for start- and end-nodes and via-points, the routing order and the cross-sectional dimensions of the hoses. The script contains IPS functions for generating the routing automatically by utilizing their built-in path-planning algorithms and simulations for calculating stresses as well as measurements of the hose segments in terms of lengths and clearance, developed by Hermansson et al. (2016).

With an implementation case provided by a car manufacturer (collaborating in the research project), consisting of three hoses with two different cross-sectional dimensions routed within the same space in the engine compartment of a car, the framework was tested. From two optimization runs using different settings (one in which one via-point per hose was optimized and the other in which two via-points were optimized), solutions similar to the original solution could be found among the Pareto optimal solution set. Figure 6 shows the centerlines of the hoses in a set of solutions generated in an optimization, depicting how the design may vary within the solution set.

Figure 6 *Centerlines of the hoses in a set of solutions generated in an optimization.*

3.1.4. CONCLUSION

The developed method and framework have shown credibility in being able to generate a set of Pareto-optimal hose-routing assemblies, including solutions similar to the original solution in the implementation case. This means that a holistic solution can be generated while decreasing the number of iterations in the development process, with automation of the repetitive tasks involved in the process. This is a result of the framework enabling the unbiased evaluation of multiple objectives at once. The design space exploration enabled by the framework can contribute to valuable additions to knowledge during

the early design phases. This knowledge is enclosed in the Pareto front, which leaves room for the engineers to take the final decisions and adjust the final detailed design.

There are, however, a few limiting aspects to the framework in this state. It does not include the dynamic simulations that are possible with the simulation software used in the implementation (IPS). These would add significantly to the required computational power of the optimization. Instead, these simulations could be run after the optimization to evaluate the candidates chosen by the engineers. The method and framework developed here provides one way of defining the placements of the via-points, but it is with certainty not the only way. Other ways of defining the optimization problem could increase the quality of both the solutions and the framework (in terms of aspects such as computational efficiency and user interaction).

The strengths of this framework and proposed method are that it is generic and modular and can thus be used as a configurator, suitable for use in several and continuous development cases, as well as for applications other than vehicles, without major modifications. The development has been conducted iteratively with a car manufacturer, including testing and evaluation by the engineers. In a later iteration based on this work (Gustafsson, Persson and Tarkian, 2021), the method has been further developed and implemented into a state where it becomes a complementary tool to the method traditionally used.

3.2. MASS CUSTOMIZED SPIRAL STAIRCASES

The e-FACTORY research project has been a collaboration with a set of small- and medium-sized enterprises (SMEs) developing and manufacturing customized products. In these companies, the large amount of resources required for each customer has been identified as an issue which limits their ability to provide product customization in a competitive way. Therefore, they are in need of automation in their product development processes. Spiral staircases constitute one such product, which is engineering intensively for each individual customer, and developed and produced by one of the industrial partners in the research project. This section is a summary of the work presented in papers B, C and D.

3.2.1. CASE BACKGROUND

Designing and delivering spiral staircases requires customer-specific input and a high degree of customization, which in turn requires extensive engineering resources for each customer order. The product can be classified as an ETO product, containing a set of both standard and nonstandard components that can be designed in an infinite number of possible ways.

At the company studied, the process from sales to delivery is currently rather complex and error prone. A major reason for this is the design challenges for each sales case. These design challenges consist of the adaption to the customer-unique context and surroundings, ensuring the fulfillment of national legislation

(e.g., the dimensioning for a capacity for emergency exits, or child proofing), the fulfillment of internal building standards and having a minimum required headroom clearance (for being able to walk upright on the staircase). The requirements are met by configuring a set of parameters of the staircase, as illustrated in Figure 7.

The other major factor leading to complexity and errors in the process is the inadequate information handling, communication and decision-making involving the customers and between the departments from sales to delivery, including design and production. This communication and decision-making is often characterized by misconceptions and assumptions, and the crucial expert knowledge is often decentralized and limited to key employees. Rationalization and integration of the process from sales to delivery of spiral staircases would enable the process to classify as a mass customization setting, with the benefits of customer responsiveness, saved resources, shorter delivery times and lower costs, due to a faster and less error-prone process.

Figure 7 Adjustable parameters for one stair segment.

3.2.2. THE PRODUCT CONFIGURATION SYSTEM

The proposed approach to achieve an efficient customization process in this project has a wide scope, spanning the sales, design and production departments. The developed solution is a product configuration system (PCS) integrating the process from sales to delivery. This PCS contains a product configurator for the order quotation stage, a CAD configurator for generating detailed models of the design and an enterprise-wide configurator for determining the final design of concurrent sales cases at the order recognition stage. The overall PCS is illustrated in Figure 8.

The order quotation stage contains a product configurator which generates a set of design alternatives given a set of customer requirements as input. When an order quotation has been accepted by the customer, that order is collected, together with other accepted orders, daily for further detailed configuration. The detailed configuration of the accepted orders is configured in the enterprise-wide configurator in a coordinated manner in order to optimize the overall delivery times and costs of the multiple orders. In between these stages, the CAD configurator can be utilized to generate detailed models of the design alternatives for each order.

Figure 8 Overall process from order quotation to order recognition of the PCS.

PRODUCT CONFIGURATOR

The core of the PCS is the product configurator, which is aimed for the quotation stage of the process, and developed to support the initial sales instance. The use of a configurator here ensures feasibility in the solutions provided for each customer's requirements and context, generating reliable quotation content.

To enable the rapid generation of sales alternatives that the sales situation requires, the product model has been constructed as computational models. These models generate a blueprint of the staircase design. For cost estimations, the parts most influencing the total price can be extracted and calculated. To generate the sales alternative with the product model, an optimization algorithm is used. The optimization formulation consists of two objectives; the first regarding minimizing the material costs of the staircase and the second is maximizing the quality of the staircase in terms of its usability. The usability factor are based on the sizes of the landings, headroom clearance and ergonomically desirable relation between step depth and width. The complete problem formulation is presented in Paper C.

In the implementation of the product configurator, the optimization problem formulation has been solved using a OpenMDAO implementation (Vidner, 2021) of NSGA-II (Deb et al., 2002). The MOO formulation results in a Pareto frontier from which a subset of alternatives is extracted. These constitute the design alternatives for the quotation at the sales stage.

CAD CONFIGURATOR

The CAD configurator is used to enhance the fidelity of the design alternatives with complete CAD models in SolidWorks, in order to be able to generate a complete bill-of-material (BOM) and other production preparations. The CAD configurator is built on HLCt, utilized by instructions in an XML-file exported from the product configurator. For this application case, this is one of the central building blocks in the ability to offer the spiral staircase as a CTO product, which requires little to no engineering activity.

ENTERPRISE-WIDE CONFIGURATOR

An enterprise-wide configurator is used at the order recognition stage to concurrently adapt the final design for the order quotations that have been accepted at the time. The purpose of this configuration is to elect those final designs according to the current status of the supply chain, meaning increasing

profit, maintaining stock levels and decreasing delivery times. This is achieved by evaluating different possible combinations of design alternatives with an optimization algorithm (the optimization formulation can be seen in Paper D). The optimization formulation contains two objectives. The first is the delivery time for the total quantities of each component in a combination of design alternatives that needs to be manufactured (i.e. that exceeds the set minimum stock balance levels), which is minimized. The second is the manufacturing cost to be minimized for all components in a combination of design alternatives. Just as for the product configurator the optimization formulation is solved with using the OpenMDAO implementation (Vidner, 2021) of NSGA-II (Deb et al., 2002).

3.2.3. RESULT

To test the PCS, previous sales cases provided by the collaborating staircase manufacturer were used. The product configurator was used to generate design alternatives for seven such customer cases of varying sizes and application contexts. Of the ten orders per case that were selected as design alternatives, solutions similar to the original solutions were included for each case, showing that the product configurator is able to generate solutions corresponding to those the sales personnel and engineers had previously done.

Using those same cases, the enterprise-wide configurator was tested (seven orders with ten alternatives each). The results of the optimization performed indicate that the overall delivery times could be reduced with up to 66 %. For solutions where delivery time is shorter, components in the configurations of the solution are well distributed by the availability in the stock levels, and where manufacturing is still necessary, they are manufactured at production work centers where the lead times are relatively short. The modeling of the enterprise-wide configurator facilitates the possibility of a scenario in which a customer might be offered a staircase of higher material value than what they are actually paying for, as a result of the fact that co-producing it with the other orders reduces the total manufacturing for a certain combination of design alternatives of the set of orders.

3.2.4. CONCLUSION

The PCS developed and demonstrated on spiral staircase integrates the process from sales to delivery. The process is extensively rationalized by the use of design automation, design optimization and enterprise-wide

optimization. Resources can be more efficiently utilized, benefiting both the customer and the retailer. At the initial sales stage, customer requirements are captured and verified in order to generate design alternatives that are feasible for the unique customer context, which thereby enables the rapid generation of correct quotations based on verified data. At the order recognition stage, the enterprise-wide configurator can determine the detailed design concurrently with other accepted orders. This means that, using this PCS, the design of the products is adapted according to the state of the concurrent sales and the supply chain of the company, rather than adapting the supply chain to the design of the products. Determining the final product design in this way shows potential for significant reductions in delivery times and maintained stock levels, demonstrating how enterprise-wide optimization may be implemented to enable mass customization.

DISCUSSION

This discussion chapter first brings up the general limitations of the work conducted which is then followed by a discussion of aspects of the developed configurator systems both in general and from application case-specific points of view. These aspects reflect the topics of the research questions of the thesis which are: the technical aspects of applying optimization in configurators to achieve automation (in RQ1) and the effects of these configurators on the product development process (in RQ2).

4.1. LIMITATIONS

Within this thesis, the approach of automating the design tasks of the product development process with optimization-enabled configurators has been applied to two industrial application cases. These application cases are quite dissimilar, both in the type of product and the processes within which they are developed and produced. In the first case, involving hose routing in vehicles, the product itself is complex and the configurator developed is aimed at only one component group among the many components that the vehicle contains. The product development process is extensive for this type of product, and the configurator has been developed to assist a limited part of that development process. In the second case, concerning the spiral staircases, the

complexity instead lies in the configuration process, which is unique for each new customer, and must be efficient enough to enable mass customization efficiency.

Due to the diversity of the application cases, as well as their limited number, the level of generalization of a single method in this thesis is limited and is a subject for future work. Instead, two different methods are presented as possible approaches to automation in the search for efficient product development. They constitute a demonstration of one solution, rather than the solution itself. Furthermore, some simplifications of the product models have been made in order to demonstrate some of the proofs-of-concept and are thus to be seen as only indicating results. The number of test data for the optimization runs used to generate the presented results is another limitation.

Product development and design research involves multiple disciplines in interaction. Not all of these have been the primary focus of this thesis, such as user interaction with the configurators.

4.2. OPTIMIZATION IN CONFIGURATORS TO ACHIEVE AUTOMATION

The frontier for what an intelligent system can achieve is constantly pushing forward, which is why design automation systems need to keep up. In this thesis, this is attempted by placing configurators in the spotlight. Product configurators are often discussed in a sales context, especially for mass customization. This thesis, however, addresses configurators outside the scope of mass customization and highly customized products. Configurators may be seen as a broader concept than just product configurators. The definition of a configuration is “the particular arrangement or pattern of a group of related things” and “the way in which something, such as a computer system or software, is organized to operate”^a. For this reason, the concept of the application cases is discussed in this thesis under the term configurator. In both application cases, the configurators are used to arrange a setup of components to operate in a specific context, given a specific set of inputs. This also resonates with the way in which design optimization approaches work, to evaluate configurations by considering different values of the design variables.

a. Cambridge dictionary definition of “configuration.”

Thus, pairing configurators and design optimization is not a far-fetched match. The challenge is to make it work in practice.

A further core element implied in the definition of a configurator is that it is not a single-use tool. Therefore, a configuration system must be set up to handle continuous cases where the different contexts and requirements mean that the limits or intervals of the design variables, constraints and objective functions change from case to case when utilizing optimization for them (for example, the number of floors and the surroundings of the staircase, and the number of hoses in the engine compartment of a vehicle). Configurators need to be built to handle multiple disciplines in order to generate the kind of holistic solution required for complex products with complex development processes. Thus, a challenge is the modeling of disciplines that are not as trivial to evaluate as others, for example the ergonomics of the assembling of hoses in manufacturing. A challenge alongside the complexity of the problem formulation of the optimization in the configurator, is the computational efficiency. This consideration is context dependent. For example, where the configurators are used in a sales context, it is of great importance to generate solutions quickly. Where configurators are used in a longer development process, as for cars, the lack of instant generation of solutions can more easily be worked around, for example by running the optimizations outside of working hours.

In the application cases studied in this thesis, optimization has been an enabling tool to automate the design tasks and processes, where the nature of the products or components are not suitable for modularization due to the number of degrees of freedom and the design space being infinite and/or complex. Design automation itself has the clear benefits of resource efficiency, where optimization can aid in the extension of automation to product customization design processes. More specifically, this means a systematic search of the design space in order to efficiently find feasible and optimal values of the design variables of the configuration. Furthermore, when using MOO formulations, multiple alternative designs can be generated and presented, which can serve as a basis for decision-making by engineers and customers, or as input for enterprise-wide optimization.

4.2.1. APPLICATION CASE: HOSE ROUTING

The reason why optimization has been a successful approach in this case is that the complexity, including the multiple objectives and considerations of

disciplines as well as the degrees of freedom in the components, is high. Using a procedural, rule-based approach to a fully modularized product architecture in order to automate the task would lead to a solution in which only one hose at a time is optimized, which can be achieved with the simulation software utilized in the developed framework. The number of degrees of freedom of the hose routing task facilitates the possibility of defining the geometrical definition of the design variables in many different ways and is something that is a possible improvement area to investigate in future work. However, the configurator is not aimed at generating a solution that is better (in terms of the objectives of the case) than what the engineers would be able to develop without the configurator. Instead, the aim is primarily to generate a good enough solution to save resources and reduce the repetitive work in the development process.

4.2.2. APPLICATION CASE: SPIRAL STAIRCASES

The approach to enabling this type of product for mass customization has not been to use the traditional approach of a rule-based procedural configurator based on a solely CTO product setup. A procedural configuration process would result in possibly unfeasible and non-optimal solutions, or may require employee-bound intuition and knowledge. To be able to offer mass customization of the spiral staircases, they must retain their ETO design. Therefore, optimization has been used as the solution to do so. Furthermore, in the second iteration of the research project the development has advanced to an approach in which the PCS contains a second configuration process, where several orders are considered concurrently. The motivation behind the development of this second configuration lies in the uncertainty in the quotations generated at the initial sales stage, in terms of when, and if, these will be accepted by the customer. The state of the production line, stock levels and concurrent sales orders will all change from the time of the quotation being made to the time of the order being accepted (which can be a timeframe of months). Thus, the delivery time is at this point calculated using more reliable and accurate ERP-data. This demonstrates the opportunity of further advancing the intelligence of a PCS for mass customization, but ultimately requires that the product is of such a kind that the range of options presented to the customer during the first stage all satisfy the customer's requirements but still vary across a range wide enough to actually impact upon the objectives of the concurrent optimization at the enterprise-wide level.

4.3. EFFECTS ON THE PRODUCT DEVELOPMENT PROCESS

Introducing and employing the configurator systems, such as those developed for the application cases in both examples, places demands on the organizational adaption to it. The tools and methods imply changes in parts of the ways in which the product development process to a larger or smaller extent. With the organizational adaption in place, the company's departments become integrated in the process, and can reduce the necessary amount of resources, repetitive work, errors and manual information handling. With a more efficient process, increased customization or mass customization can be achieved.

In both cases, the configurator systems do not replace the engineers. They have been developed as tools for decision-making support by systematically exploring the design space and providing knowledge earlier in the process. This enables engineers to make informed decisions during that crucial part of the process, and also affects the level of customization and flexibility that can be achieved in the products developed. The systematic design space exploration can serve either to provide conceptual solutions in a more efficient manner or to solve complex sales cases with verified fulfillment of requirements. In both cases, the available knowledge is increased earlier in the process. Long-term quantitative evaluation of the effects of the product development process is something that needs to be further evaluated and validated in future work.

4.3.1. APPLICATION CASE: HOSE ROUTING

The products for which the hose routing is intended are not ETO products and have a long way to go before they can be a possible mass customized product. Cars are for example a customized product but built up of pre-defined components and configurations equivalent to a CTO product. However, using design automation tools with flexible configurator functionality in more parts of the overall product development process of this segment of products may be an enabler for increasing the customization level. The configurator developed for this application case reduces the number of iterations needed in the development process, and increases the available knowledge earlier in the process, which may save a significant amount of valuable resources.

4.3.2. APPLICATION CASE: SPIRAL STAIRCASES

One of the major effects on the product development process in the

spiral staircase case is the integration of knowledge and the elimination of assumptions, which reduces the uncertainty in the estimations made during the sales stage based on inadequate information. This makes the quotation process faster and more accurate, which is a basis for mass customization. The system integrates all the departments, from sales to delivery, which poses challenges to adapt the organization accordingly. The enterprise-wide configuration approach also means that a large amount of data needs to be coordinated and maintained. From a research perspective, this is an important aspect of enabling this coordination and maintenance as the system is scaled up, which should be investigated in future work.

CONCLUSIONS

In this thesis, two application cases have been studied. The first concerns hose routing in vehicles. For this case, a configuration system has been developed that automates the engineering-intensive task of routing hoses in the engine compartments of vehicles. The implementation of this system as a proof-of-concept configurator has proven it able to generate solutions close to the reference solutions developed by engineers at the collaborating company, using a reduced amount of resources through the achieved design automation.

The second application case concerns spiral staircases as a subject for possible mass customization. Here, a two-stage configurator system has been developed to rationalize the currently complex and error-prone customization process at a collaborating company. The implementation of this product configuration system has demonstrated that the utilization of optimization is an effective tool to automate the configuration process, thus supporting the enabling of mass customization.

The work of this thesis is concluded below by answering the two research questions raised at the beginning, in a generalized and condensed way.

5.1. ANSWERING THE RESEARCH QUESTIONS

RQ1. Why is the utilization of optimization in configurators suitable for

achieving automation for engineering-intensive configurable products?

Optimization can be an enabler in constructing effective configurators to automate the configuration process for products where traditional rule-based CTO approaches are not suitable. This may be because the nature of the product contains complex interrelations that are non-predictable using procedural configuration approaches. There, optimization algorithms can do the job of finding suitable configurations for each specific case that is configured. Furthermore, changes in the product design and architecture needed in traditional CTO approaches can be avoided using optimization-based configurators, since the existing product design and architecture is retained. Setting up the configurator to be optimization-based may also save time, as it avoids the need to explicitly define all the configuration steps and applied rules, as is required in a rule-based configurator. However, when employed, the configuring process itself is likely to be more time-consuming using optimization, due to the design space search performed by the optimization algorithm.

The utilization of optimization provides systematic design-space exploration that is necessary to achieve automation of the design processes associated with configurable engineering-intensive products. This implies that increased flexibility of the product design can be achieved without compromising quality or lead time. In conclusion, the use of configurator systems can be extended using optimization with adaptable formulations for continuous development cases.

RQ2: How would the utilization of optimization in configurators affect the product development process for engineering-intensive configurable products?

Developing and employing configurators implies that the process is rationalized, which in turn leads to reductions in repetitive work, errors, misconceptions and estimations. Overall, this means that the product development process can be more efficient and effective, making it more responsive to increased customization.

The systematic design-space exploration provided by the optimization increases the available knowledge early in the process, when it is crucial for the utilization of available design freedom and mass customization. This

knowledge can then be used as decision support in the form of trade-off design alternatives by the use of MOO formulations. This knowledge is also integrated between the departments of a company, affecting it at an organizational level. The extension of the configurator systems to also consider enterprise-wide data, such as stock levels and production lead times, is a further level of knowledge integration and coordinated decision-making that contributes to further leveraging the possibilities of product configurator systems.

5.2. FUTURE WORK

As the optimization-based configurators in this work are applied to only two application cases, important future work is to implement such configurators in further cases. This will enable a higher level of generalization and conclusions, as well as the detection of their limitations. Both for the application cases in this thesis and for further cases, a more thorough evaluation of the employment and use of the configuration systems should be made using quantitative measures to investigate their effects in the product development process. This also includes the development of user interfaces to support the employment of the configurators.

Currently, the software and toolboxes for implementing flexible optimization formulations are limited in their abilities, which is why future work may also include the development of software and algorithms to support the development, employment and maintenance of the optimization-based configurators. This includes supporting abilities to handle variations in the optimization formulations (e.g. varying the number of design variables and/or their limits) as well as the integration of systems that may be part of the PCSs (e.g. ERP-systems, CAD software and graphical user interfaces). It also concerns the efficient adaption of optimization algorithm settings to the varying configuration cases.

As of now, the enterprise-wide optimization aspects have only been developed in a limited context, with limited data and scope. Thus, extending and further developing the enterprise-wide optimization aspects of configurator systems is also a subject for future work.

Lastly, the scope of this work focuses on exploring the potential of optimization to extend the use of configurators, without proposing this approach as replacement for configurators taking rule-based procedural approaches.

Therefore, future work could also address refining the criteria for when the optimization approach is most appropriate and when other approaches are more suitable, considering the advantages and disadvantages in set-up time, the product design changes needed and the context of use of the configurator.

REFERENCES

Amadori, K. et al. (2012) 'Flexible and robust CAD models for design automation', *Advanced Engineering Informatics*, 26(2), pp. 180–195. doi: 10.1016/j.aei.2012.01.004.

Andersson, J. (2000) 'A survey of multiobjective optimization in engineering design', Tech. Rep. Linköping University: Department of Mechanical Engineering, Linköping.

Beasley, D., Bull, D. R. and Martin, R. R. (1993) 'An overview of genetic algorithms : Part 1, fundamentals', *University Computing*, 2(15), pp. 1–16.

Blessing, L. T. M. and Chakrabarti, A. (2009) *DRM, a Design Research Methodology*. London: Springer London. doi: 10.1007/978-1-84882-587-1.

Cederfeldt, M. and Elgh, F. (2005) 'Design automation in SMEs - Current state, potential, need and requirements', *Proceedings ICED 05, the 15th International Conference on Engineering Design, DS 35*, pp. 1–15.

Chapman, C. B. and Pinfold, M. (2001) 'The application of a knowledge based engineering approach to the rapid design and analysis of an automotive structure', *Advances in Engineering*

Software, 32(12), pp. 903–912. doi: 10.1016/S0965-9978(01)00041-2.

Deb, K. et al. (2002) 'A fast and elitist multiobjective genetic algorithm: NSGA-II', *IEEE Transactions on Evolutionary Computation*, 6(2), pp. 182–197. doi: 10.1109/4235.996017.

Elgh, F. (2012) 'Decision support in the quotation process of engineered-to-order products', *Advanced Engineering Informatics*, 26(1), pp. 66–79. doi: 10.1016/j.aei.2011.07.001.

Fogliatto, F. S., da Silveira, G. J. C. and Borenstein, D. (2012) 'The mass customization decade: An updated review of the literature', *International Journal of Production Economics*, 138(1), pp. 14–25. doi: 10.1016/j.ijpe.2012.03.002.

Forza, C. and Salvador, F. (2002) 'Managing for variety in the order acquisition and fulfilment process: The contribution of product configuration systems', *International Journal of Production Economics*, 76(1), pp. 87–98. doi: 10.1016/S0925-5273(01)00157-8.

Forza, C. and Salvador, F. (2008) 'Application support to product variety management', *International Journal of Production Research - INT J PROD RES*, 46, pp. 817–836. doi: 10.1080/00207540600818278.

Franke, N. and Piller, F. (2003) 'Key research issues in user interaction with user toolkits in a mass customisation system', *International Journal of Technology Management - INT J TECHNOL MANAGE*, 26. doi: 10.1504/IJTM.2003.003424.

Fraunhofer Chalmers Center (2021) Industrial Path Solutions (IPS). Available at: <http://www.fcc.chalmers.se/software/ips/>.

Giesling, J. P. and Barthelemy, J.-F. M. (1998) 'A Summary of Industry MDO Applications and Needs', in 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization., pp. 1–20.

Goldberg, D. E. (1989) 'Genetic Algorithms in Search,

Optimization, and Machine Learning'. Boston, MA, USA:
Addison-Wesley Publishing Company. ISBN: 0201157675

Gounaris, C. E. and Grossmann, I. E. (2019) 'A preface to the special issue on enterprise-wide optimization', *Optimization and Engineering*. doi: 10.1007/s11081-019-09468-9.

Grossmann, I. (2005) 'Enterprise-wide optimization: A new frontier in process systems engineering', *AIChE Journal*, 51(7), pp. 1846–1857. doi: 10.1002/aic.10617.

Gustafsson, E., Persson, J. and Tarkian, M. (2021) 'Combinatorial Optimization of Pre-Formed Hose Assemblies', in 47th Design Automation Conference (DAC). ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference: American Society of Mechanical Engineers (accepted)

Haug, A., Hvam, L. and Mortensen, N. H. (2011) 'The impact of product configurators on lead times in engineering-oriented companies', *AI EDAM*, 25, pp. 197–206. doi: 10.1017/S0890060410000636.

Heikkinen, T. (2021) 'Extended product models supporting multidisciplinary design automation'. PhD diss., Jönköping University.

Hermansson, T. et al. (2016) 'Automatic Routing of Flexible 1D Components with Functional and Manufacturing Constraints', *CAD Computer Aided Design*, 79, pp. 27–35. doi: 10.1016/j.cad.2016.05.018.

Hopgood, A. A. (2001) *Intelligent Systems for Engineers and Scientists*. Second Edi. Taylor & Francis Group. ISBN: 0-8493-0456-3

Huang, G. Q., Simpson, T. and Pine II, B. (2005) 'The power of product platforms in mass customisation', *Int. J. of Mass Customisation*, 1, pp. 1–13. doi: 10.1504/IJMASSC.2005.007348.

Hvam, L., Mortensen, N. H. and Riis, J. (2008) *Product Customization*. Berlin Heidelberg: Springer-Verlag.

Johansson, J. (2011) 'How to Build Flexible Design Automation Systems for Manufacturability Analysis of the Draw Bending of Aluminum Profiles', *Journal of Manufacturing Science and Engineering*, 133, p. 061027. doi: 10.1115/1.4005355.

Klushin, G., Fortin, C. and Tekic, Z. (2018) 'Design Optimization of Size-Adjustable Parts', *DS 96: The 20th International DSM Conference*, p. 159-169.

La Rocca, G. (2012) 'Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design', *Advanced Engineering Informatics*, 26(2), pp. 159–179. doi: 10.1016/j.aei.2012.02.002.

Meyer, M. H. and Lehnerd, A. P. (1997) *The Power of Product Platforms: Building Value and Cost Leadership*. New York Free Press. ISBN: 1451655304

Myrodia, A., Kristjansdottir, K. and Hvam, L. (2017) 'Impact of product configuration systems on product profitability and costing accuracy', *Computers in Industry*, 88, pp. 12–18. doi: 10.1016/j.compind.2017.03.001.

Persson, J. and Ölvander, J. (2019) *Engineering Optimization*. Technical Report. Linköping University: Department of Machine Design, p. 142.

Piller, F. (2004) 'Mass Customization: Reflections on the State of the Concept', *International Journal of Flexible Manufacturing Systems*, 16, pp. 313–334. doi: 10.1007/s10696-005-5170-x.

Rudberg, M. and Wikner, J. (2004) 'Mass customization in terms of the customer order decoupling point', *Production Planning and Control*, 15(4), pp. 445–458. doi: 10.1080/0953728042000238764.

Salvador, F., Martin de Holan, P. and Piller, F. (2009) 'Cracking the Code of Mass Customization', *MIT Sloan Management Review*, 50(3).

Shafiee, S., Hvam, L. and Haug, A. (2019) 'Comparing the Gained Benefits from Product Configuration Systems Based on Maintenance Efforts', in *Proceedings of the 21th International*

Configuration Workshop. University of Hamburg.

Simpson, T. W. (2004) 'Product platform design and customization: Status and promise', *AI EDAM*, 18(1), pp. 3–20. doi: 10.1017/S0890060404040028.

Sjøbakk, B., Thomassen, M. K. and Alfnes, E. (2014) 'Implications of automation in engineer-to-order production: a case study', *Adv. Manuf.*, 2(2) p. 141-149. doi: 10.1007/s40436-014-0071-4

Sobieszczzanski-Sobieski, J., Morris, A. and van Tooren, M. (2015) *Multidisciplinary Design Optimization supported by Knowledge Based Engineering*. West Sussex: John Wiley & Sons, Ltd. ISBN: 978-1-118-49212-3

Tarkian, M. (2012) *Design Automation for Multidisciplinary Optimization - A High Level CAD Template Approach*. Linköping University. Available at: <http://liu.diva-portal.org/smash/get/diva2:556208/FULLTEXT03>.

Tomiyaama, T. (2007) 'Intelligent computer-aided design systems: Past 20 years and future 20 years', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, 21(1), pp. 27–29. doi: 10.1017/S0890060407070114.

Tseng, M. M., Jiao, J. and Merchant, M. E. (1996) 'Design for Mass Customization', *CIRP Annals - Manufacturing Technology*, 45(1), pp. 153–156. doi: 10.1016/S0007-8506(07)63036-4.

Ullman, D. (2009) *The Mechanical Design Process*. McGraw-Hill Education (McGraw-Hill series in mechanical engineering). ISBN: 9780072975741.

Ulrich, K. T. and Eppinger, S. D. (2012) *Product Design and Development*. Fifth Edit. New York: McGraw-Hill. ISBN: 978-0073404776

Usma-Alvarez, C. C., Fuss, F. K. and Subic, A. (2014) 'User-Centered Design Customization of Rugby Wheelchairs Based on the Taguchi Method', *Journal of Mechanical Design*, 136(041001). doi: 10.1115/1.4026029.

Verhagen, W. J. C. et al. (2012) 'A critical review of Knowledge-Based

Engineering: An identification of research challenges', *Advanced Engineering Informatics*, 26(1), pp. 5–15. doi: 10.1016/j.aei.2011.06.004.

Vidner, O. (2021) 'OpenMDAO-NSGA: NSGA-II and NSGA-III implementations for OpenMDAO'. Version v0.1. doi: 10.5281/ZENODO.4279483.

Wang, Y. and Tseng, M. M. (2009) 'Mass customisation as a collaborative engineering effort', *Int. J. Collaborative Engineering*, 1(2), pp. 152–167. doi: 10.1504/IJCE.2009.027444

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-176088>

FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology, Licentiate Thesis No. 1914, 2021
Department of Management and Engineering

Linköping University
SE-581 83 Linköping, Sweden

www.liu.se