On Configuration Systems in Product Development for Mass Customisation

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It was the dead of night as two grand full moons stood in the sky with reproachful frowns.

'How fast are we driving now?' I asked.

'Ninety-six,' said Adriaan and carelessly turned the wheel three full rotations.

'Where are we driving now?' I asked.

'Round the market square in Rittenburg,' said Adriaan.

'Rittenburg is a beautiful old town,' I said. 'It has a sightly medieval town hall, with a monumental staircase.'

'No,' I said, when the noise had ceased, 'it had a sightly medieval town hall. Now look what you've done! You can't go up these monumental stairs by car!'

'Is this your vehicle?' the officer asked.

'Was,' we said, as we shook off the remains.

*Translated from: Huizinga, L., Adriaan en Olivier.
Amsterdam, P.N. van Kampen & Zoon N.V., 1939.*

FOREWORD

We find Adriaan and Olivier in a peculiar position, as their car has just disintegrated on ascending the monumental staircase of Rittenburg's town hall. Surely you, the reader, would agree that their choice of automobile seems highly inadequate for their midnight adventures. But then, what car would be suitable? Given the choice, these twins would require a car that seats two, has a minimal top speed of ninety-six kilometres an hour, handles adequately at said velocity, allows for in-car dialogue at conversational volume, and most importantly, is capable of ascending monumental staircases damaging neither car nor stairs. These twins are not the richest, in fact, they are essentially penniless. So how would a car manufacturer meet their requirements, and at an acceptable cost at that? And what if others, twins or not, would require a similar car for entirely different adventures, with an entirely different set of requirements?

The 1930's were very different times, pre-dating digitalised product development and automation as we know it today. But like Adriaan and Olivier, customers in today's highly competitive global market continuously seek individualised solutions, producing a demand for highly customised products in vast numbers and pushing companies to continuously improve their processes to stay competitive. The answer? Mass customisation. "Very well, but how would you do it?", you may ask. As luck would have it this licentiate thesis is the result of years of research, by yours truly and his many predecessors, towards answering that very question. Surely a room full of experts, boasting thirty years of experience each, would do the trick of designing a product for every possible situation. There is however a distinct chance that they would be preoccupied elsewhere. So, what if we let computers do the legwork, and leave actual design to the engineers and their creativity? This is where design automation and product configuration come in. Hopefully this work sheds a few rays of light upon product configuration systems, and how these can support product development for mass customisation.

Bonne lecture!

ABSTRACT

Increased industrial interest in mass customisation causes designers and manufacturers to seek cost-effective methods to continuously rationalise product development and production processes in order to accommodate for customisation on a large scale. Particularly in the case of complex products this requires significant engineering efforts.

Mass customisation in an engineer-to-order context includes customers in early stages of product development, providing designers and manufacturers with certainty in decision making. A large portion of design tasks associated with design and production preparation stages during the product development process are routine-like and repetitive, amounting to vast time costs and errors. By utilising knowledge-based design automation techniques, these tasks can be supported to allow for iterative design processes as well as improved integration and communication between development phases. This work explores how the use of design automation in the form of product configuration systems can facilitate integration throughout the product development process of engineer-to-order products and allow the industry to rise to the challenge of mass customisation.

This licentiate thesis describes the development of a framework incorporating product configuration systems based on High Level CAD templates (HLCT) together with auxiliary design optimisation and production preparation tools. Leveraging on the reuse of product knowledge, it focuses on rapid configuration of light-weight conceptual designs for quotation in dialogue with customers, and support of detailed design and generation of production data for confirmed orders. Based on the findings from implementation of such framework in an SME context of mass customisation of spiral staircases as well as engineering education, the challenges and possibilities are discussed with an eye on the future of design automation for mass customisation.

ACKNOWLEDGEMENT

Thanks to all for their help, and to myself for daring to ask for it.

APPENDED PUBLICATIONS

This foundation of this licentiate thesis is comprised of the following papers, referred to by their Roman numerals. These are appended in their original state, bar minor errata.

- I. Poot, L. P., Wehlin, C., Tarkian, M. and Ölvander, J. (2020) 'Integrating Sales and Design: Applying CAD Configurators in the Product Development Process', *Proceedings of the Design Society: DESIGN Conference*. Cambridge University Press (CUP), 1, pp. 345–354.
- II. Wehlin, C., Vidner, O., Poot, L. P., Tarkian, M. (2021) 'Integrating Sales, Design and Production: A Configuration System for Automation in Mass Customization', in *ASME 2021 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC-CIE 2021)*.
- III. Poot, L. P., Tarkian, M. and Ölvander, J. (2021) 'Design and Production Automation for Mass Customisation – an Initial Framework Proposal Evaluated in Engineering Education and SME Contexts', in *28th ISTE International Conference on Transdisciplinary Engineering, TE2021*.
- IV. Poot, L. P., Gustafsson, E., Tarkian, M. and Ölvander, J., 'Machine Learning for Computer-Aided Design in the Product Development Process: A Structured Review', in manuscript.

ADDITIONAL PUBLICATIONS

The following paper is, while published during the course of the research and constituting an important part of its background, not included or discussed in this licentiate thesis.

- V. Poot, L.P., Johansen, K. and Gopinath, V. (2018), 'Supporting risk assessment of human-robot collaborative production layouts: A proposed design automation framework', *Procedia Manufacturing*, Vol. 25, pp. 543–548.

AUTHOR CONTRIBUTIONS

Poot is the main author of paper I and III, responsible for both manuscript and presentation in communicating the research findings, providing support and feedback as co-author of paper II. Main authorship and contributorship of paper IV are shared between Poot and Gustafsson.

Contribution to paper I and II, including development of methods and proof-of-concept frameworks, and analysis and interpretation of results, consists of a joint effort between Poot, focusing primarily on product configuration, and Wehlin (I, II) and Vidner (II), focusing on design optimisation. paper III includes contributions from Tarkian in course development in the role of course examiner, with particular contributions to development and analysis of production preparation methods.

All research presented in papers I-III has been conducted in the context of research project e-FACTORY¹. Research presented in paper IV has been conducted in the contexts of e-FACTORY and AutoPack², both initiated by Tarkian. Co-authors Ölvander (I, III, IV) and Tarkian (I-IV) provided support and feedback as subject matter experts and in their respective roles of supervisor and co-supervisor.

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² AutoPack (Ref. nr. 2017-03065) funded by Vinnova through the partnership program Strategic Vehicle Research and Innovation (FFI).

LIST OF ABBREVIATIONS

ATO	Assemble-to-Order
CAD	Computer-Aided Design
CODP	Customer Order Decoupling Point
DRM	Design Research Methodology
ETO	Engineer-to-Order
HLCt	High-Level CAD templates
KBE	Knowledge-Based Engineering
MTO	Manufacture-to-Order
MTS	Manufacture-to-Stock
PCS	Product Configuration System
PDP	Product Development Process
SME	Small to Medium-sized Enterprises

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1 INTRODUCTION

Increased industrial interest in mass customisation of products causes designers and manufacturers to seek cost-effective methods to continuously rationalise product development and production processes in order to accommodate for customisation on a large scale. Particularly in the case of complex products this requires significant engineering efforts. This licentiate thesis describes how the use of design automation in the form of product configuration systems (PCS) can facilitate integration between all phases of the product development process (PDP) and allow the industry to rise to the challenge of mass customisation.

1.1 BACKGROUND

Mass customisation is defined by Davis (1989) as “using new technologies to deliver mass-produced goods and services to individuals on a tailorised basis and mass scale simultaneously”. In practice, this boils down to adapting one or several designs of a product into variants using both standardised and newly designed or modified components in order to meet unique requirements from individual customers, while variants are expected to share core functionalities.

The type of mass customisation setting varies depending on whether a variant can be produced in its entirety from pre-made components, requires new or re-designed components, or a combination thereof. In manufacturing terms, the point in the value chain where the manufactured product is tied to a specific customer is known as the Customer Order Decoupling Point (CODP), dictating the turning point between speculative and certain decisions, (Rudberg and Wikner, 2004). The earliest of such, known as engineer-to-order (ETO), includes customers in the engineering process allowing for the highest level of customisation (Levandowski et al., 2015) and is key to customisation of highly complex products.

In this thesis, case studies are discussed of design automation applied to products manufactured in large quantities, retaining the same core functionality yet requiring unique customer-specific adaptations. While this type of design automation for mass customisation is not applicable to unique cases such as one-off products or projects such as highly specialised research vessels or nuclear powerplant designs, the cases in the thesis focus mainly on application in the staircase industry, where (spiral) staircases are mass-customised to fit each customer’s unique requirements.

In order to identify a development process' main contributors to design errors and excessive costs, one needs look no further than the vast amount of routine-like and repetitive tasks involved (Stokes, 2001). A means of addressing such issues, mitigating errors and thereby reducing excessive costs in the process, is the implementation of design automation, applicable in each phase of the PDP from the initial explorative stages to production planning. An example is geometry automation in conceptual design stages, allowing rapid iteration between designs changes while continuously ensuring the technical feasibility of concepts. However, such automation efforts are often confined to their specific departments, disregarding subsequent and foregoing development phases, and thereby missing the possibility of holistically rationalising the entire PDP.

While the research in this thesis is not applied in an Industry 4.0 setting, it adheres to similar goals and leverages the same abilities. Industry 4.0, first introduced in Germany in 2011 (Xu et al., 2018), is on one hand the answer to a market pull in terms of demands on shorter development times, individualised product, flexibility in development and manufacturing, decentralization, and resource efficiency (Lasi et al., 2014). On the other hand, Industry 4.0 relies on technical concepts such as: smart factories - where assets are equipped with sensors and where manufacturing systems communicate with each other, self-organisation - i.e. the ability of assets to organise themselves in order to reach an overarching goal, cyber-physical systems - where the physical and digital level of products and systems merge and blend together, and new systems for interaction between product and production development that facilitate individualisation (Lasi et al., 2014). The recent developments of technologies such as sensors, Internet of Things, digitalisation in a broad sense, artificial intelligence (AI), machine learning etc. are all enablers for Industry 4.0. The presented framework is intended to leverage the automation and the intelligence of manufacturing systems offered by Industry 4.0, in order to ensure that the development processes and the designed products utilises the benefits offered by the next generation of manufacturing systems.

The design automation discussed in this thesis builds on several methods, connected and intertwined within the applied frameworks. Stakeholders involved in the PDP, being design or production engineers or salespersons depending on the current maturity of the product, come directly in contact with the incorporated configurators. These build largely on knowledge-based engineering (KBE) methods aimed at automating repetitive and non-creative design tasks and can incorporate the use of advanced automation techniques such as design optimisation algorithms in different development stages. Towards later stages, automation tools are utilised to translate design

features into production data, moving the product towards manufacturing and assembly. Critically, the possibility to take a step back and reiterate any or all design stages must be ensured.

1.2 AIM

The aim of this thesis is to explore the future of design automation and product configuration and pinpoint the requirements for implementation in the larger scheme of the PDP in mass customisation and ETO settings. To this end, key characteristics to successful implementation of PCS are investigated based on industrial case studies. With this in mind, the thesis delves into methods of extending the reach of design automation-based configuration beyond the confinements of traditional design stages, with the aim of exploring methods capable of rationalising larger part of the PDP. Finally, the thesis seeks to explore future directions for production configurations systems in the light of recent developments in digitalisation and AI.

The above aims are captured in the following research questions:

- RQ1. What are the key characteristics to successful implementation of product configuration in mass customisation contexts?*
- RQ2. How can product configuration be extended from traditional product design to include phases such as sales and production preparation?*
- RQ3. How can design automation and product configuration leverage artificial intelligence?*

1.3 METHODOLOGY

To provide a scientific level of reproducibility and repeatability, a transparent combination of documented scientific research methods is adopted. The main methodology is in accordance with the design research methodology (DRM) framework as suggested by Blessing and Chakrabarti (2009). DRM promotes an iterative process over four stages named Criteria, Descriptive Study I (DS-1), Prescriptive Study (PS), and Descriptive Study II (DS-II), described in short in Table 1.

Table 1 – Design research methodology stages (Blessing and Chakrabarti, 2009)

Criteria	Identification of measurable criteria based on objectives and goals
DS-1	An understanding of influential factors obtained through observations and analysis
PS	Development of methods and tools based on assumption and experience
DS-2	Evaluation of methods and tools, measured using the success criteria

In addition to the DRM framework, the Empirical Scientific Inquiry (ESI) approach suggested by (Roozenburg and Eekels, 1995) is applicable. Following a similar pattern, it suggests looping iterations where the induction of hypotheses is based on observations, from which predictions are deduced which are subsequently tested and evaluated.

Figure 1 - Empirical Scientific Inquiry flowchart, adapted from (Roozenburg and Eekels, 1995)

The studies leading up to this thesis have predominantly been conducted within the context of the research project e-FACTORY, in full named “Efficient Automation for Customised products in Swedish Industry”, with focus lying on integrating engineering activities throughout the PDP to facilitate mass customisation. These studies are presented in papers I-III. Figure 2 shows the research conducted per paper in relation to the DRM.

Paper I covers the first iteration within the project, consisting of the criteria, DS1 and PS stages. The studies follow the ESI approach with observations through review of literature and interviews forming the base of a framework subsequently developed and tested iteratively in cooperation with engineers and evaluated in an industrial setting. The studies described in paper II can be seen as the second iteration of this process with continued development and analysis of the framework, with a deeper focus on design optimisation. Further research within the same context is presented by (Vidner et al., 2021). The studies presented in appended paper III are a continuation of papers I and II, with focus on production preparation. In addition to the

industrial context, implementation is simulated and evaluated in an engineering education setting. Furthermore, this research includes a structured literature review aimed at partly answering research question 3. This study focuses on identifying contemporary usage of machine learning in combination with CAD in the PDP and is reported in appended paper IV.

Figure 2 – Appended papers in relation to DRM stages

1.4 OUTLINE

Concluding this introductory chapter, the remainder of this thesis is structured as follows. In the second chapter the frame of reference is outlined, diving deeper into the concepts of mass customisation and design automation, and illustrating their state of the art based on relevant contemporary literature. The third chapter describes the research conducted, highlighting its place in the context of the frame of reference. The findings are subsequently discussed in the penultimate chapter. Finally, this work is brought to a close in the concluding chapter, summarising the thesis with the aim of answering the aforementioned research questions with an eye on future research.

2 FRAME OF REFERENCE

The giants upon whose shoulders this thesis stands are the bodies of research in design automation and mass customisation in product development, and the methods developed to achieve these described in contemporary academic literature. This chapter sets the frame of reference for the studies in this thesis, by describing mass customisation and design automation in relation to the PDP, and how knowledge-based methods can form the base for configuration systems aimed at facilitating mass customisation.

2.1 PRODUCT DEVELOPMENT

The PDP is, as the name suggests, the process of developing a product from its very first conception to a tangible, functional product. Throughout the years, research has resulted in numerous models describing the necessary steps to take and tasks to perform for efficient product development. Models of the PDP are frequently divided into specific phases, each including specific tasks.

While the exact extent and naming of each differs between models, Howard et al. (2008) categorise the comprising phases as the analysis, conceptual design, embodiment design and detailed design phases. These are most often preceded by a need establishment phase, and ultimately followed by an implementation phase typically involving production-related tasks. Authors of these models seemingly agree in their understanding of what the PDP entails, with minor differences in naming and description of phases. Ulrich and Eppinger (2008) for example, do not explicitly include the earliest establishment of needs but denote the analysis phase as the starting point, dubbed strategic planning, while their implementation phase is divided into testing & refinement and production ramp-up. Others are more generic problem-solving models, such as Cross' (2008) model consisting of its' exploration, generation, evaluation, and communication phases, or the slightly more elaborate product innovation process model by Rozenburg and Eekels (1995).

According to Howard et al. (Howard et al., 2008), the apparent linearity of many traditional PDP models causes these to poorly translate to real-life creative processes. The sequential manner in which the phases are described may work well in educational settings due to their simplified presentations of the PDP, and allow an industrial adopter of the model to recognise and set gates for each phase, but result in what is referred to as "over-the-wall-

engineering” (Owens, 2001). This can compromise the efficiency of the process, as communication between phases, or rather engineers and departments responsible for these, is hampered. Other, non-linear methods address this by including iteration within and between phases. See for example concurrent engineering (Prasad, 1996) and agile product development (Thomke and Reinertsen, 1998).

2.2 MASS CUSTOMISATION

Mass customisation is, as Davis introduced it under the term “mass customizing” (Davis, 1989), “more than an intriguing oxymoron”. The core visionary idea involves the design and production of products for the mass market, while retaining the possibility to tailor each individual product to the needs of every customer at a cost close to that of traditional mass production. The vision grew from mere concept to a promising strategy for select markets by the turn of the century and had within the following decade become a widely implemented and researched strategy capable of provided considerable competitive advantages. Key factors for mass customisation are flexibility in both product design and processes, and integration between actors throughout the supply chain. (Da Silveira et al., 2001; Fogliatto et al., 2012). Mass customisation of products can build on several methods such as modularisation (Ericsson and Erixon, 1999) and platform-based product families (Jiao et al., 2007; Levandowski et al., 2015), and design platforms for early technological development (André et al., 2017).

The level of individualisation differs per product, depending on customer requirements. Da Silveira et al. (2001) describe eight generic levels of mass customisation between fully individually designed products to pure standardisation: design, fabrication, assembly, additional custom work, additional services, packaging and distribution, usage, and standardisation. The level to be applied is naturally dictated purely by customer demand, and each merits its own unique selling points. In the case of mass customisation of complex engineering products through PCS, the top three levels of customised design, fabrication and assembly are key.

In order for a product to be customised, customers must be involved at minimally one point in the product realisation process (Simpson, 2004). The point in the value chain at which the product becomes irrevocably tied to a specific customer is denoted as the CODP, described by Rudberg and Wikner (2004) as the point after which decisions can be made under absolute certainty. Upstream from the CODP, the manufacturer bases its decisions on speculation, whereas downstream activities relate to known specifications. The CODP is at times known as the order penetration point (OPP) (Olhager,

2003). Rudberg & Wikner (2004) note that most literature describes four distinct possible positions of the CODP in a linear continuous model of a value chain. In order of level of customisation possible, these are typically denoted as engineer-to-order (ETO), manufacture-to-order (MTO), assemble-to-order (ATO), and manufacture-to-stock (MTS), with the resulting process named after the CODP involved. ETO includes the customer at the earliest of all four, allowing full customisation of a product, while MTS purely relies on retail activity, with the customer simply choosing between readily produced variants. Whereas ETO is often denoted as such, the remaining processes are also known as modify-to-order, configure-to-order, and select-variant, respectively (Hansen, 2003).

The CODP is traditionally linked to production, with engineering seen as an upstream activity. Wikner and Rudberg (2005) note that in the case of mass customisation, engineering and production may function concurrently and describe instead a two-dimensional view on the matter, with engineering and production each acting as a separate dimension as shown in Figure 3. As per this description, ETO stands out as a special case of MTO, shown as ETO_{ED}. In this two-dimensional space, integration between engineering and production becomes feasible, regardless of the position of the CODP in the production dimension. As such, configuration of products and variants is possible in both MTO_{PD} and ATO_{PD} settings, or any combination thereof. To facilitate mass customisation of complex engineering products, an ETO approach is required to include the customer in the early stages of the PDP, allowing for the high level of customisation required in such a setting (Levandowski et al., 2015).

Figure 3 – Two-dimensional CODP plane and examples of CODP positions, adapted from (Wikner and Rudberg, 2005)

2.3 DESIGN AUTOMATION

The aim of design automation is, according to Elgh (2007), to support the triptych of design synthesis, design analysis, and plan for manufacture, each fitting in the embodiment and detailed design phases of the PDP. This is accomplished by “implementation of information and knowledge in solutions, tools, or systems, that are pre-planned for reuse” (Cederfeldt and Elgh, 2005, p. 2). Utilising design automation, an efficient process can be adopted by automating the non-intuitive and non-creative design tasks, allowing time to be spent on value-adding (customisation) tasks while decreasing the overall time-cost and minimising errors. Repetition and accuracy are after all the very essence of automation. This frees the engineer from their creative bonds, allowing them to spend their valuable time to iteratively perfect their concepts and explore the boundaries of the design space.

2.3.1 Computer-Aided Design

CAD has, since Ivan Sutherland introduced SKETCHPAD as he presented his Ph.D. dissertation at MIT in 1963 (Sutherland, 1963), had continuous impact on product development to the point where three-dimensional modelling and analysis is now widely accepted and de facto standard throughout the engineering industry. Sutherland’s tool was a landmark for computer graphics, human-computer interaction, and even parametric control of geometry. Over the years, tools became more and more powerful, as engineers were able to create shapes with not only basic geometry but advanced, mathematically defined free-form curves and surfaces. Through the seventies and eighties, CAD continued to grow increasingly more powerful and emerged as commercial software. With the advent of personal computers throughout the nineties came software capable of running on such platforms along with new attempts to standardise formats, spreading CAD far and wide, and by the end of the millennium solid modelling was everywhere (Tornincasa and Monaco, 2010). Today, it is nigh on impossible to imagine the development of any product without CAD being the core enabler for design, analysis, and production preparation.

Whereas CAD has undeniably helped the creation, analysis, and production of increasingly sophisticated and complex products immensely, Stokes (2001) states that approximately 80 per cent of design tasks can be repetitive and routine-like. This allows errors to creep into the designs due to the tedious nature of these tasks (Tarkian, 2012), an inevitable problem now that CAD lies at the heart of contemporary product development. Hence the immense benefits of CAD systems have enabled unprecedented complexity in design, to the point where the usability of these systems has become a hindrance.

This could, in part, be addressed by design automation and KBE, and by extension product configuration. Willner et al. (2016) estimate that up to 90 per cent of total engineering time may be saved by integration of CAD systems with PCS.

2.3.2 Knowledge-Based Engineering

Knowledge attained throughout the development process forms a valuable basis for KBE, a method of capturing and reusing knowledge of both product and process with the aim of reducing resource consumptions by automating repetitive, non-creative tasks, and enabling multidisciplinary design optimisation through a combination of CAD and AI. Reuse of product knowledge is promoted by embedding it into tools such as CAD applications during the conceptual phase, allowing for the information to be transferred to later stages of development. (Chapman and Pinfold, 2001; Rocca, 2012). Expert systems based on KBE build on inference engines that can abductively solve design problems in vague domains which are either poorly measured or partly hypothetical in nature based on configuration goals and boundaries set by an engineer (Menzies, 1996). In essence, these tools are told to find a “best possible” solution based on the gathered expert knowledge.

2.3.3 Knowledge Carriers in Design Automation

A CAD model may function as the primary carrier of knowledge in design automation, accomplished by extending models beyond a product’s core geometric features. Techniques for achieving this range from supplementary parameters and attributes, independent or linked to specific CAD objects, to dedicated geometric objects required for analysis, and embedded code to be interpreted by external programs (Heikkinen et al., 2018).

A practical method of utilising CAD models as knowledge carriers is the adoption of High Level CAD templates (HLCT), as proposed by Amadori et al. (2012). These allow for the inclusion of both geometric and non-geometric information to be stored in stand-alone templates, The template database, together with a knowledgebase based on the non-geometric information and a dedicated inference engine, form a flexible product configuration platform. In contrast to creating variants by activating components in overpopulated, often computationally expensive models (‘110 per cent principle’), HLCT act as building blocks capable of adapting contextually to one another, allowing greater freedom in generating models of customised products. This structure resembles that of knowledge objects described by (Johansson and Elgh, 2019), combining humanly legible knowledge representations, be it in the form of geometry or non-geometric attributes such as text, with information dictating the application of said knowledge by means of an inference engine. HLCT is applied throughout the studies described in this thesis.

Despite its central role in the PDP, a CAD model may be unsuitable depending on the type of knowledge and associated automation task. Non-geometric knowledge may for example be carried by stand-alone KBE systems, or managed with spreadsheets. (Johansson et al., 2018) The later can include rules governing geometry automation of connected CAD models, with formulas and programmed routines acting as the inference engine.

2.4 PRODUCT CONFIGURATION SYSTEMS

Implementation of mass customisation is often approached through product configuration, aiming at translation of customer requirements to the product information while adhering to pre-set rules for product variants (Salvador and Forza, 2004). The use of product configurators dates back to the computer system configuration program R1 (McDermott, 1982), evolving into a field of considerable interest in both industry and academia (Zhang, 2014). In a mass customisation setting, where phases can be repeated throughout the PDP, development of a product's variants can be considered as stand-alone development processes. A large part of the activities within these phases involves computer-aided design. In conceptual phases configurators can aid the design of customer-specific variants (Trentin et al., 2012).

PCS are, as defined by Hvam et al. (2008), IT systems capable of supporting sales, design, and production preparation of customised products. Such systems are powerful, if not essential, tools for mass customisation, paving the way for accurate and efficient establishment of quotations and product specifications (Hvam et al., 2008). High accuracy of quotations is essential for a manufacturer's continued competitiveness, as stated by Elgh (2012).

Many will have come across web-based sales configurators for products such as personal computers, cars, and footwear, three common examples in literature concerning business-to-consumer mass customisation. A common theme is the goal to not only fulfil a utilitarian function, but also appeal to individuals' desire for uniqueness and self-expressiveness, the perception of which is impacted by the design of the configurator itself. (Sandrin et al., 2017) Their CODP lies production-wise between ATO and MTO, resulting in a configuration process of medium to medium-high complexity according to Piller & Blazek (2014). Provided that a consumer configures within the boundaries of the allowed design space without the addition of extraordinary requirements, little to no additional engineering is required after an order is placed. This stand in contrast with the type of product discussed in this study, often requiring engineering activities despite similar production CODP's, raising the level of complexity.

2.4.1 Impact of Product Configuration

A configurator is one of the most successful and widespread examples of AI implementation in the engineering industry (Haug et al., 2011), adopted by large companies as well as small and medium-sized enterprises (SME) alike (Zhang, 2014). Academic interest in the field remains at a high, as the industry continues to push towards customisation and increasingly powerful tools emerge to facilitate digitalisation. Use of configurators beneficially affects lead times, product quality, product knowledge preservation, cost estimation accuracy, product profitability, certainty of delivery, customer satisfaction and the time required to train personnel (Haug et al., 2011; Kristjansdottir et al., 2018b). A significant decrease in product lead times has been evidenced from the implementation of configurators, with decreases in working hours per product even amounting to 75 per cent (Kristjansdottir et al., 2018a).

2.4.2 Challenges of Product Configuration

Whereas it is evident that PCS are a powerful addition to the industrial arsenal of product development tools, a lack of understanding of the challenges involved in implementation can severely impact their outcome. Kristjansdottir et al. (2018b) state that knowing of challenges is one thing, but that it is essential to understand the relative importance of each type of challenge. According to their findings from both literature and interviews with industrial players, product-related challenges are secondary in importance to challenges in organisation and knowledge acquisition. The complexity of the product itself has, therefore, less of an impact upon the success of a configuration-centred design process than knowing precisely what types of input and output are expected, and how the design process is handled by all stakeholders. It is essential to maintain a level of flexibility in the system; a product configurator must facilitate inclusion of additional or replacement components, so that the accessible design space remains apparent. Continuous control and maintenance of the system is required for a stable and profitable system (Gorski et al., 2016), for which flexibility is key (Trentin et al., 2012).

2.4.3 Existing Product Configuration Systems

While a company might develop in-house design automation tools, a number of tools are commercially available with the aim to facilitate design automation and product configuration, easing the transition into a design automation powered PDP. These may either come in the form of stand-alone applications or as modules as part of a larger configure-price-quote (CPQ) system, a term more frequently encountered in the industry than in academia. (Sorri et al., 2017)

Examples of commercially available software focusing on configuration utilising forms of geometry automation and KBE, stand-alone or as part of an Enterprise Resource Planning (ERP) or CPQ system, are DriveWorks³, XperDi CAD Configurator (XCC)⁴, and Tacton Configurator⁵. Similarly, CAD vendors and developers have in recent years added KBE tools to their CAD systems such as Creo⁶ and SolidWorks⁷. XCC in particular has been an integral part of the industrial-academic projects studied in this thesis, being originally based on HLCT demonstrated by Amadori et al. (2012).

In industry today, success stories exist from companies having both developed in-house design automation tools as well as applied the commercial existing counterparts. However, challenges remain, such as described by Kristjansdottir et al (2018b). It is thus paramount to investigate how an understanding of the characteristics of a product, and the configuration process surrounding it, impacts its development in a mass customisation setting.

³ DriveWorks Ltd, www.driveworks.co.uk

⁴ XperDi AB, www.xperdi.com

⁵ Tacton Systems AB, www.tacton.com

⁶ PTC Inc., www.ptc.com

⁷ Dassault Systèmes, www.solidworks.com

3 CONFIGURATION FOR MASS CUSTOMISATION

Before attempting to build a configuration structure, it is of utmost importance to understand the proverbial “ins and outs” of the configuration process; quite literally, the available input data and required output data. Is the resulting configurator to be used solely as a tool to ease modelling tasks? Or is it to be integrated in a larger framework, connected to up- and downstream activities? To what degree will the product be subject to customisation, and what does this mean in terms of modelling? This chapter attempts to clarify these questions and provide pointers as to how to answer them, summarising the findings from studies conducted in the context of the research project e-FACTORY and described in papers I-III.

Figure 4 – Spiral staircase parameters affecting usability

3.1 STAIRCASE STUDIES

Spiral staircase design is the main subject of the studies described in papers I and II. While the product itself may not be considered highly complex, its design process in a mass customisation setting is. Every staircase is as unique as the building it is designed to fit, forcing the development process to accommodate a high degree of customisation. In the production dimension of Wikner and Rudberg's (2005) two-dimensional CODP space, the CODP_{PD} of these spiral staircases lies between MTO_{PD} and ATO_{PD}. Staircases are configured from a set of standardised ATO_{PD} components, such as the steps, with MTO_{PD} components to accommodate for their placement, such as the central pillar and landings. While the landings can be adapted from pre-defined designs, central pillars must be designed and manufactured anew for each new staircase. In select cases, designs may require additional adaptations, such as alteration of components to clear obstructions in a building.

With success being very much dependent on early customer input and translation thereof into design parameters such as those illustrated in Figure 4, the CODP lies close to ETO_{ED} in the engineering dimension due to the complexity of the configuration process required. While a number of standardised, predesigned, and premanufactured components are used, the configuration process of an entire staircase is very much customer-dependant and full of design challenges. Due to the nature of stairs, uncertainty concerning for example the exact segment height requirement from floor to floor could put an entire order on hold. Even a slight change in segment height will require steps to be moved along the central pillar, as their vertical spacing, h , must remain even for the stairs to be feasibly walkable. Larger differences in height may require addition or subtraction of steps, affecting their rotation along the pillar, their tread depth, α , and the depth of the landing, β . This in turn requires redesign of the railings, further complicating the matter. The approximate position in the CODP space is illustrated in Figure 5.

The mass customisation process of spiral staircases from sales to delivery has been studied primarily in collaboration with a Swedish manufacturer of stairs and related products. In its current state, the process is deemed time-consuming and error prone, with the main contributing factors identified during the studies being the design complexity of each unique order and communicational difficulties.

Figure 5 – Approximate CODP of spiral staircases in this study, in red

The design challenges, as hinted at with the aforementioned example concerning segment heights, extend beyond mere customer-induced complexity. While a staircase design must first and foremost fit the context and surroundings governed by the building and its obstructions, its designer must ensure that it fulfils safety requirements dictated by national legislations and building standards. Examples of such are minimum unobstructed height constraints for sufficient headspace, maximum opening sizes and other childproofing measures, or specific geometric requirements for means of egress. On top of these constraints, specific geometric ratios governing stair ergonomics are to be taken into consideration, depending on intended use, often directly affecting the total cost of materials.

Communicational difficulties affecting the process originate partly from misunderstandings in direct contact with customers due to product complexity. However, a non-negligible portion stems from inadequate information management between design phases and subsequent misinterpretations and assumptions. While this is certainly not unusual in a setting where success relies on the knowledge and experience of individuals with distinct areas of expertise, introducing a means of translation between their respective languages can streamline the process. Utilising design automation, and product configuration in particular, this translation can be supported between sales, design, and production. Thus, the PDP can be rationalised through integration between the development phases and their respective personnel, mitigating errors and decreasing costs in the process.

Figure 6 – Product configuration framework adapted from paper I

3.2 CONFIGURATION FRAMEWORK

The framework for a product configuration system proposed in paper I contains a duet of two configurators, aimed at quotation with conceptual design and detailed design with production preparation, respectively, as depicted in Figure 6. Its structure is a direct result of the initial findings from observations of the aforementioned sales and design processes for spiral staircases. Following the PDP from left to right, it shows the phases of sales, conceptual design, detailed design, and production preparation with two separate configurators facilitating the design tasks of and communication between the phases. In sales and conceptual design, a Conceptual Configurator is used with an embedded multi-objective optimisation module to generate and iterate over designs for quotation to the customer.

The resulting data is used in detailed design by a Detailed Configurator to generate a complete CAD model of a chosen design, used during Production preparation through numerous modules to generate production data. The remainder of this subsection describes the framework's set of tools for each stage and their interconnectivity.

The use of multi-objective optimisation algorithms is an integral part of the described framework and the studies leading to its development and implementation. For a deeper understanding of the optimisation module's inner workings, the reader is kindly referred to the works of Vidner et al. (2021) and Wehlin (2021), in addition to the optimisation-specific sections of paper II.

3.2.1 Conceptual Design Stage

The use of a separate configurator in the sales and conceptual design stage stems from the requirement for rapid feedback to customers as identified during the spiral staircase study. In acceptance of the fact that embodiment and detailed design require more time than the window of customer contact allows, the product is simplified to a high degree of abstraction. Representing the most crucial aspects of a spiral staircase design in mathematical form, the lightweight mathematical model allows for conceptual configuration without requiring computationally expensive modelling.

The Conceptual Configurator consists of a graphical sales interface, with backend modules for constraint validation, design optimisation, and design generation. The knowledgebase describes known constraints based on safety standards and the like, the interconnection of expected customer requirements contra design parameters, and a cost model relying on data from an ERP database. With customer requirements provided to the interface, the configurator translates these into a set of design parameter values. If deemed valid after comparison against the constraint knowledgebase, the design optimisation module is allowed to apply its intelligence to search the design space while continuously testing the results against all given criteria. Finally, lightweight graphical interpretations and data of designs deemed optimal are generated and fed back to the interface as a set of concepts, complete with cost estimations. Depending on the nature of the chosen optimisation algorithm and the depth to which it is allowed to explore, this process can take from mere seconds to a few minutes. From a chosen concept and its data, a quote can be created for the customer to finalise the order quotation stage. This is illustrated in the left part of Figure 6. For a more detailed explanation, see paper I.

3.2.2 Detailed Design Stage

The next phase in the PDP is initiated using the design specifications generated during the order quotation stage once the quotation for the chosen conceptual design has been accepted. In the detailed design stage, the CAD-based Detailed Configurator is utilised to generate accurate three-dimensional models based on the design specifications of the conceptual design, as illustrated in the *Detailed Design* section of Figure 6.

The Detailed Configurator follows a design automation by KBE approach, consisting of an inference engine, an accompanying knowledgebase and a database of templates based on HLCt by Amadori et al. (2012). The design specification is translated into the design parameter values expected by the inference engine as prescribed by the knowledgebase. The components described in the specification are instantiated from the HLCt and adapted topologically and morphologically where applicable according to the design parameters. The result is a complete CAD model, with all information relevant to subsequent stages extracted from the HLCt and embedded, describing for example production related properties.

3.2.3 Production Preparation Stage

Provided that all necessary production methods are known to their full extent, and their requirements and limitations have been duly considered during design, generation of production data will build entirely on data introduced in earlier development stages. Furthermore, in a mass customisation setting, a configured product will consist of variants of known components. Without unknowns interfering with development, the process of generating production data of design variants can thus be seen as copying specific features from design to production-specific formats. As Patton and Patton (2009, p. 313) put it: “anything that can be copied can be copied automatically”, provided a complete design.

The information embedded in a fully configured model forms the basis for direct translation of a design into production data using the components' geometry together with both geometric and non-geometric application-specific reference data. Such embedded information may come in the form of textual information on choice of material, coating or choice of paint colour, or geometry, pointing out preferred contact points and directions for support structures in assembly. Examples of generated data include production orders, production drawings, assembly instructions, and machining code, each requiring application-specific modules to be included in the framework as illustrated at the far right in Figure 6. Such modules will require a dedicated inference engine with accompanying knowledgebase but can, through the embedded information, share databases with upstream

configurators. The flexibility of the applied HLCT-based configuration method provides for maintenance of the entire framework, crucially allowing inclusion of new production geometry in templates as production preparation modules are added, without impacting the configuration process itself.

3.2.4 Case Study Results

As a continuation of the studies described in papers I and II, adaptations of the framework implemented at three industrial research partners show promising results as described in paper III. At the time of writing, configurators have been implemented in the detailed design process of all three companies, with accompanying production preparation modules for production data, including automatic generation of drawings and CNC instructions. Integration of design and sales through configuration is in development, with focus lying on web-based interfaces. The main takeaways are in line with the aim of the framework and design automation as a whole, confirming a higher resilience against errors creeping into products throughout the PDP and lowered overall costs. One company estimates up to 90 per cent reduction in administrative time costs from quotation via order registration, purchasing, and control of stock balance to technical documentation.

3.3 KEY CHARACTERISTICS FOR CONFIGURATION

To successfully build a PCS around a specific product one must understand the key features and variables that enable this. Naturally, each and every type of product has a distinct set of features, requiring a unique configuration set-up. While the digital tools and methods used may be the very same for very different products, templates and knowledgebases must be defined for each product (family) before configuration can commence.

A product must contain a number of specific characteristics to be configurable; and more importantly, for configuration to be a cost-effective design method, it is of utmost importance to know the intended usage of the system and the limits within which a designer must be able to navigate the design space. The configuration process relies on standardisation of the product's components themselves and their database templates as well as the geometric interface. Ultimately, standardisation will limit the level of customisation achievable, but allow reuse of components, products, and knowledge concerning their design. It is therefore important to understand where in the CODP space the majority of a product's realisation process is to be situated early in the process of creating and populating the database, the backbone of any PCS. Depending on the level of customisation, templates may

be required to allow for morphological changes, topological changes on component or product level, or a combination thereof.

3.3.1 Database Ingredients

A purely ATO_{PD} product will require little to no morphological changes to configured components, sweeping the road towards a comparatively easily configured product. The result is a purely combinatorial problem with a database composed of fully defined components. As all possible incompatibilities will be known prior to order, no additional engineering is required past the CODP to complete delivery of the product. CAD models of such products' components can easily be encased in templates and included in a configuration database with little more effort required than the addition of information concerning their positioning in space and the product hierarchy. Such PCS can then be utilised to design and simulate placement of possible new components, for continuation of ATO_{PD} or a shift towards higher degrees of customisation. A product focusing on higher levels of customisation will require a far larger effort in order to create a sufficiently flexible template set and corresponding knowledgebase. Without sufficient planning, one can find oneself limited by the configuration framework itself, harming the product line, company, and customer in the process.

3.3.2 Configuration Recipe

For a component template to be configurable and placeable within the context of a product, a number of required features must be included. Following the HLCT method, templates must include component geometry, geometry dictating topology and/or morphology of the component in context, and design parameters controlling any customisable geometry. To complete the knowledgebase of the PCS, non-geometrical information is required, dictating the component's hierarchical position in context. Additionally, the templates may include reference geometry for subsequent analysis stages as well as any subsequent child components' topology and/or morphology. For subsequent analysis and production stages, both reference geometry and non-geometrical information can be embedded. Examples include information on choice of material, coating or choice of paint colour, or geometry pointing out preferred contact points and directions for support structures in assembly.

3.3.3 Implementation

Implementation of the framework described above to the case of mass customisation of spiral staircases is described in appended paper I. Central to the entire endeavour stands the CAD configurator used in the detailed design section of the framework. The structure of the database and knowledgebase are based primarily on information gathered from numerous workshops and

interviews with the company, creating an essential overview of the intended CDP and level of customisation per component. The hierarchy of components plays a large role in this process, as the product is configured sequentially with each child component based on one direct parent, dictating the need for reference geometry and its location across the database. Thus, the structure of the configuration process mirrors the structure of the product itself. With this knowledge, population of the HLCT database is based on a combination of existing CAD models and newly modelled or adapted geometry.

Figure 7 -Illustrative view of the building blocks of HLCT for configuration of spiral staircases. To the left a HLCT structure consisting of geometry and supporting parameters, to the right four distinct geometries stemming from HLCT and a configured model of a staircase.

Figure 7 illustrates the structure of a HLCT database, four distinct template geometries, and a staircase model designed and modelled using the described framework. With staircase design customisation as an example, steps are considered standard ATO_{PD} components, with each type of step offered in a set variety of lengths. For these, their existing CAD geometry is simply placed in a new document, its topological position manipulated based on parameters for height and angle, and reference geometry modelled after the central column of the staircase. Additional parameters to be read into the knowledgebase are included, specifically stating the type of step and which parent component it can be configured to, in this case it being the central pillar or a previous step. Reference geometry for any additional step is based on the original geometry and follows the same positional manipulations. One template is created for each step in the company's catalogue, the only difference being the geometry of the component itself and the name. The

central column, handrail and certain types of, landings however, require more intricate templates, as these components are uniquely engineered to each design, with the added complexity of morphological modification. The template structure equals that of the steps, but where those could simply include existing non-parametric geometry. These ETO_{ED} templates require parametrically adjustable geometry. The geometry of the handrail, for instance, builds on standardised balusters positioned according to the height and rotational position of each step, and the template must therefore take this context into account using reference geometry provided from its parent component.

3.4 CONFIGURATION AND SALES

Configuration does not necessarily apply exclusively to the traditional design stages of the PDP, as is evident from the framework depicted in this thesis. With a suitable level of abstraction, and in cases even without visible geometry, the reach of design automation and the configuration it enables can extend the process upstream to include customers and sales personnel before traditional design tasks commence, as shown in papers I and II. Whereas detailed, and therefore computationally expensive, digital models are required to truly dot the i's and cross the t's of a product, simplified models can be used to successfully gather customer requirements. Unimpeded feedback to the customer or personnel directly in contact with customers is essential in this stage, to ensure that the product and its requirements are understood by all affected parties and any discrepancies can be iterated over and removed without frustration.

Any error resulting from miscommunication in the very first stages of a product's development may result in increased time-costs downstream, unsellable manufactured products, and loss of goodwill. To this end, a configurator can be used in mass customisation settings as a communication tool to mitigate misunderstandings resulting in such errors, with near-instant feedback providing a base for confirming the customers' requirements and intentions with the product. Often a visual representation can be of great help, where a product may meet hard criteria such as specific measurements and functional values, yet fail to satisfy perhaps assumed "soft requirements".

Paper II describes the placement of the PCS within an overarching framework utilising multi-objective optimisation towards enterprise-wide optimisation (EWO), a strategy involving optimisation of operations throughout the supply chain. Originating as an area of research in chemical process engineering, a key feature of EWO is integration of information and thereby coordination of decision-making and activities across all stages (Grossmann, 2005). Gounaris

and Grossmann (2019) state the goal of EWO as “minimisation of costs, responsiveness to customers, asset utilisation, management of inventory levels, and the improvement of a supply chain’s ecological footprint” through sophisticated IT tools.

Figure 8 – Enterprise-wide optimisation and configuration in order quotation and recognition stages, paper II.

To minimise delivery time and production costs enterprise-wide, multiple conceptual design alternatives for each in a set of accepted quotations are collected, together with an overview of current lead times in production and stock balances. Comparison between designs and their components in juxtaposition with the current state in production is utilised by the optimisation algorithm to point out each order’s optimal choice of design. The result is a set of designs which, while crucially continuing to fulfil customer requirements, makes optimal use of standardised components currently in stock and manufacturing resources. Figure 8 illustrates the position of configurators in such an EWO framework. Similar to PCS, key to the success of such an EWO framework is maintained flexibility, entertaining the introduction of new products and solutions as well as organisational changes.

3.5 CONFIGURATION AND PRODUCTION

As the configuration scope is extended upstream towards sales processes, similarly the scope can be extended downstream; with the correct features included in the configurator's template database and appurtenant knowledgebase, automated production planning based on the configured product can bridge the gap between design and production and further rationalise the entire process. Paper III describes further studies on the aforementioned framework for integration between design and production preparation, incorporating several post-design modules automating tasks requiring copying and translation of design features to production data. The framework is put into context in an advanced course at Linköping University, with the intended learning outcomes including understanding of the correlation of digital models with reality, the use of customer data to drive development of customised products, and the suitability of different digitalisation methods depending on the type of product. Not only does this provide research with much-needed results from what are essentially small-scale simulations, it equally provides the students, and through them their future employers and colleagues, with an understanding of modern tools and strategies applicable in both research and industry.

Run in project-form with the application or product to be chosen by the students, and thus without pre-defined answers, the course builds on open-ended problems. Projects are selected based on level of complexity and realism to appropriately simulate industrial cases. With focus shifted away from sales to production, each project results in a proof-of-concept version of the framework described in section 3.2, incorporating conceptual design, detailed design, and production preparation stages. Snapshot impressions of several student projects' results in generating drawing features, two-dimensional CNC layouts, and robot programming for assembly are shown in Figure 9.

The hypothetical case to which the projects adhere involves concepts being presented by a customer or design department in the form of a mock-up, in physical form, requiring its shape to be digitised through three-dimensional scanning or in digital form requiring other means of translation to CAD-friendly formats. A configuration system for further conceptual design and detail design is built based on the HLCT methodology. In the templates, data required for specific production methods is included. Subsequently, auxiliary modules are programmed for generation of production data. Production in this case incorporates laser-cutting sections from MDF sheets and assembly using robotic arms. For this, each product must be adapted and sectioned into planar geometries to be assembled.

Figure 9 –Examples of student project results from implantation of a production-focused configuration framework, from paper III

Data required for two-dimensional manufacturing applications such as laser- or waterjet cutting can be rendered in a similar manner to production drawings by generating vector paths, provided that the product is designed with such manufacturing in mind. CAD software generally includes drafting modules, allowing for fast generation of two-dimensional paths from three-dimensional models, viewed from specified viewpoints. Positioning a multitude of such two-dimensional paths within a specified area, however, requires an experienced user or application of optimisation algorithms in order to minimise manufacturing time and/or material. Robot offline programming software can be used in order to automatically generate robot programs for automated assembly. For more details on the extension to downstream activities, such as production preparation, see paper III.

4 DISCUSSION

The development and implementation of the described framework in the staircase case has shown the importance of product configuration in communication within a company as well as with external stakeholders, e.g. customers. This chapter discusses the limitations of the presented research, and the challenges and opportunities identified in configuration for mass customisation, before providing an outlook on possible improvement of the framework and implementation of emerging AI techniques.

4.1 LIMITATIONS OF STUDIES

A limitation of this work is the limited number of industrial application cases studied. While this has allowed profound studies, with several iteration cycles of development and analysis of the methods and proof-of-concept tools, it naturally limits the extent of possible generalisation from the results. Whereas the complete framework has been evaluated in an industrial setting in workshops together with industrial partners, it has not been evaluated to its full extent. Additionally, the cost-benefit balance has not been considered. However, the application of the proposed framework in an educational setting, with multiple various projects, supports the hypothesis that the framework is generalisable and applicable both in and beyond the case company. This calls for further studies on the implementation and in-depth evaluation of similar frameworks in the development of additional products or mass customisation settings, with a sufficient breadth of organisational and design challenges to allow for a generalised understanding of the impact of such frameworks and any alterations they may require in order to have a measurable impact in the industry.

4.2 CHALLENGES AND OPPORTUNITIES IN CONFIGURATION

Human thinking is rarely rational, with humans' perception of possibilities controlled, limited, and extended by previous experiences, personal biases, and moods. Even if engineers are trained to rationalise their intuitive perception of design limitations during their education, and will inevitably extend their training both actively and passively throughout their careers, they cannot be expected to be fully aware of all feasible designs for a given set of requirements and constraints, or pinpoint the best possible alternative among them. Nor should they be expected to correctly identify equally optimal alternatives in a multi-objective context with conflicting criteria. The

use of product configurators can therefore function as an engineer's guide in the design space.

4.2.1 Configuration as a Communication Tool

Allowing for rapid iteration over concepts, the Conceptual Configurator provides the opportunity for a customer and sales representative to quickly iron out the majority of misunderstandings and mitigate the most insidious errors before more detailed engineering efforts are required. While the visualisations from the proof-of-concept shown in appended paper I do not highlight the aesthetics of designs, the most substantial factor in this is the multitude of concepts generated for each iteration. This provides a base for discussion concerning not only a design in juxtaposition with the stated requirements, but comparison between designs bringing clarity to any judgement-based requirements the customer may have. Although staircases for emergency egress from an existing building, for example, may be ordered purely based on little more than measurements, staircases intended to fulfil additional aesthetic functions will likely require more detailed visualisations. These can instead be created from the model generated in the detail design stage. While this may take hours and thus not produce such visualisations instantly, the process is deemed sufficiently swift to ensure continued responsiveness to the customer. Furthermore, the Detailed Configurator could be extended for downstream activities such as production preparation as shown in paper III.

With sufficiently fast rendering of results, an engineer or even customer can rapidly iterate on conceptual designs. This provides the possibility to explore the design space in ways rarely possible in traditional engineering within a reasonable time space, entertaining the creativity required for innovative solutions to complex design problems. With repetitive and frankly dull tasks taken care of through automation, engineers are free to test their ideas and crucially receive direct feedback on the feasibility and validity of the resulting designs. Provided that the database and knowledgebase do not include errors, none should creep into the final designs due to the configurator's embedded knowledge of feasible morphological and topological ranges and combinations, lowering the threshold towards investigating extraordinary configurations. If any errors or unwarranted limitations are found during design stages, the templates can simply be adapted, without these errors arising in any future configuration thereafter. Newly acquired knowledge can thus be incorporated in the heart of the design process, without requiring each engineer to gather enough experience to not make the same mistake twice.

With the inclusion of design optimisation in general, and multi-objective optimisation in particular, in a Conceptual Configurator, the user receives an additional tool providing not only an understanding of relative optimality between concepts, but crucially feedback on the requirements and insight into the impact of each. With such insight certain negotiable requirements could be relaxed, expanding the design space in search of the best possible design. Purely functional requirements, such as the height of a staircase segment, will be unnegotiable. Other requirements may be based on judgement rather than indisputable facts, or may even be the result of misunderstandings or preconceptions and can thus be adapted through iteration in dialogue with the customer. This further underlines PCS as a communication tool, capable of having a direct impact on overall customer satisfaction.

4.2.2 Configuration's Impact on Costs

It is undeniably important to answer customer's requests sufficiently fast to retain their interest; however, products such as the spiral staircases touched upon in these studies are rarely ordered directly after customer contact is established. Not only may customers only use an initial quotation in their decision process to choose between several products or companies providing similar products, design specifications will have to be verified and perhaps altered before an order is finalised. While the speed of the initial configuration is essential to communication, this means that detailed design stages are seldomly limited by the same time constraints and may well take longer without risking customer retention. Provided that any engineering required can be performed within an allowed time window, dependant on the type of product and industry, the essential time-related factor here is the time it takes an engineer to configure a product or verify generated designs. Even with the framework automatically generating detailed designs to specifications from the conceptual design stage, human verification of these designs is likely inevitable due to the complexity of the product. Highly unusual customer requirements may require manual design of additional components or adaption of generated designs, due to the standardisation of components required for a PCS to be viable. However, the time it takes for the inference engine to configure a product and generate its geometry is, in essence, trivial. Even the most computationally challenging configuration can be built without human interaction from a design specification, provided the database includes all necessary templates, allowing the engineer to concentrate on other tasks, take a break, or even letting the computer have at it outside office hours. Compared to manual design, this can increase productivity by an order of magnitude and reduce direct labour costs for each design.

While the notion of cost varies depending on whom is affected and how, it is in this context primarily seen from the industry's point of view as a financial loss, either directly, due to loss of materialistic or time resources, or indirectly, due to loss of reputation and reduced customer trust in the company. Additional types of costs, ranging from environmental costs to the wellbeing of personnel, may, however, require attention during a product's development and remainder of its lifecycle, as well as during the development of any PCS for that product. While inevitably important, these types of costs are not considered within the scope of this thesis.

4.2.3 Adapting to Levels of Customisation

It is of utmost importance to understand the context and goals concerning a product before attempting to build a PCS or including it in an existing PDP. It is imperative to know the extent of the limitations of design freedom the standardisation of components incurs. This is true for any modular product platform regardless of digitalisation of the configuration process, but will become more apparent when attempting to rationalise all features and setting their boundaries geometrically. While the freedom to add additional modules to the line-up or modify existing templates remains, setting the correct morphological and topological boundaries can mean the difference between errors creeping into designs and insufficient design freedom. Both will require manual alterations to any resulting design before production and additional maintenance of the database, incurring manual labour costs either way.

Knowing the required level of customisability, and thereby the CODP location of one's product, is key to forming an understanding of a PCS' requirements. Whether the return of investment for developing a PCS is worth the effort needs to be considered by balancing the cost of developing the system and the cost savings that could be gained, considering all the potential costs mentioned in 4.2.2. Configuration, or rather the development of dedicated digital tools to this end, may not be necessary or at all cost-effective at extreme levels of customisation. In the two-dimensional design space (Wikner and Rudberg, 2005), these extremes lie at either end of the engineering dimension. Any ETS_{ED} product will naturally require little to no engineering, laying the responsibility of mass customisation entirely on production and logically being unfit for configuration, manual or otherwise. In the case of entirely $[ETO_{ED}, MTO_{PD}]$ products however, the cost of predicting the majority of all possible variants and creating the required database and knowledgebase under speculation as well as any custom interface required for correctly communicating the limitations and freedom may outweigh the cost-savings achieved with the completed PCS. In such a situation it may, however, be worthwhile to select a portion of the speculated

variants with a lower breadth of flexibility required based on distinct similarities between solutions and components. The resulting PCS can thereafter nonetheless be used to configure a base for extreme variants, requiring only minimal manual adaption to fit requirements outside the limited design space of the PCS.

4.3 OUTLOOK

4.3.1 Improvement of Existing Modules for Visualisation

While studies on the implementation of the framework described in Section 3 have proven the concept in an industrial setting, several improvements are possible, and indeed necessary, before unleashing it within a company's PDP. As opposed to the Detailed Configurator, based on the HLCT methodology and utilising the flexibility that comes with it, the Conceptual Configurator relies on a highly specific model and interface with low flexibility as a result. While a form of HLCT could be applied to the models of this first stage, this would likely require adaption to a context more user-friendly than traditional CAD modelling software. This requirement is partly dictated by the intended user at this stage, who may not have experience with, or have access to, such software. For which the user experience should be as straightforward as possible. It also depends on time limitations, as the process should provide concepts sufficiently quickly so as not to interfere with communication between sales personnel and customer by keeping any of the involved parties waiting. Visual representation is key to supporting such communication, calling for representations of the product in question that enhance the comprehensibility of a design's strengths and aptly convey that the customer's requirements have been understood and met. To this end, the concept of HLCT can be applied to formats fit for game engines, for example, which due to their rendering capabilities and focus on user-friendliness could elevate the user experience by allowing a customer to experience their future product in a virtual setting, viewing and even interacting with lightweight three-dimensional geometry.

4.3.2 Weaving in Additional Disciplines and Tools

As evidenced by the studies discussed in this thesis, a framework incorporating PCS and auxiliary tools can be applied to the entire PDP, impacting each of its phases. Utilising existing tools, specifically created for their respective disciplines, should provide greater rewards than recreating these within a PCS.

Any digitalisation tool used in design today can theoretically be incorporated in a PCS, providing input to the configuration itself, analysis of a design, or manipulation of its output to fit any subsequent process relying on design data. Examples would include not only generation of production data as described above, but also automated aerodynamical or structural analysis through simulation or safety assessment and failure mode and effects analysis (FMEA), to mention a few areas to span the possible design space. However, successful incorporation of auxiliary tools relies on several factors. Practically, formats must be compatible, or at least humanly legible, to be able to translate information in between; and in cases where functions of existing software for applications such as structural simulation or additive manufacturing are to be controlled, these functions must be accessible through an API. Beyond the practical, technical implementation, it is of utmost importance to understand the discipline itself, drawing on the expertise of the original users of such tools, to be able to embed their knowledge in the PCS. In the appended papers, initial work on product preparation is presented using rather simple models as a proof of concept. Including additional models from adjacent domains is a natural direction for future work, as well as more detailed and advanced models and simulations for the included domains.

4.3.3 Incorporating Artificial Intelligence

The usage of PCS in a KBE environment together with optimisation is a clear step towards integration of AI in the PDP. Based on the rapid progress of AI with the emergence of learning-based methods, i.e. machine learning and its subsets deep learning and reinforcement learning, there is great potential in merging these achievements with the PCS proposed in this thesis. To this end, a literature review is presented in paper IV, aimed at identifying existing methods and implementations of machine learning applied to CAD.

In essence, machine learning is the study of programs capable of automatically improving with experience (Mitchell, 1997). An initial study on the usage of machine learning in relation to CAD and product development has been conducted as part of this research, reported in paper IV in the form of a structured review of relevant academic publications between 2008 and 2018. The majority of implementations in identified publications focuses on application within singular design phases, most notably in preparation for production and manufacturing from detailed design. As is the case for the role of design optimisation in the configuration framework discussed in chapter 3, machine learning implementations are generally embodied as part of a larger framework.

The majority of publications identified in Paper IV describe application of learning-based methods in the context of singular design phases, or specifically focus on integration between two adjacent phases. In particular, the detailed design phase, and tasks concerning production and manufacturing preparation, are highly represented. The frameworks included in this category are commonly applied to CAD/CAM and generally focus on regression, i.e. prediction of, for example, shrinkage in additive manufacturing, and classification, such as feature recognition for process selection. All identified frameworks for production relied on three-dimensional CAD models as input. As such, these types of implementations are more or less directly applicable to the production preparation stage of the PCS.

Frameworks identified for implementation in conceptual design phases focus partly on aiding multidisciplinary design optimisation, specifically the training of computationally effective and accurate surrogate models. These are able to replace simulation models for rapid analysis of concepts, or can be utilised to identify “soft requirements”, enabling customer preference to be included as an optimisation objective. Others focus on identifying and translating design intent between design representation- aiding design synthesis, commonly generating three-dimensional models from such formats as numerical data representing customer requirements or from two-dimensional images of hand-drawn sketches. Such examples of machine learning can be applied in the conceptual design phase, aiding the optimisation module included in the PCS. Additional identified publications describe implementations applicable throughout the PDP in a supporting role. Examples include knowledge reuse through design retrieval based on feature recognition in abstract models, automated model simplification for simulation and analysis, or object recognition applicable in production preparation.

While machine learning has had undeniable impact in many fields of research, it is important to consider its requirements before implementation. Machine learning can roughly be divided into supervised, unsupervised, and reinforcement learning. In the case of supervised and unsupervised learning, the experience from which an algorithm learns is, simply put, the data it is presented with. Supervised learning, the most common form, focuses on generalisation from pre-labelled data for classification or regression, while unsupervised learning is typically applied to discover patterns in unlabelled data (Mitchell, 1997; Sutton and Barto, 2015). Datasets for training of the algorithms are often required to be substantial in size. While artificially generated training data can be obtained from simulations, a trained algorithm will never be better than the data it has been trained on.

In contrast, reinforcement learning works iteratively by letting an agent learn from interaction with an environment, providing support for decision-making while eliminating the need for large datasets of historic data. While other forms of machine learning algorithms learn to provide predictions based on structures it has found in its training data, a reinforcement learning agent will learn a policy, a decision-making rule, from trial-and-error experiences and their rewards. (Sutton and Barto, 2015) Despite being underrepresented in the findings described in paper IV, reinforcement learning can therefore be of interest in further research in cases where available data is limited.

Ultimately, it is up to the user to decide whether or not to trust and move forward with any prediction, classification, or proposal provided by any AI tool, be it knowledge-based or learning-based. Domain knowledge is therefore required in development of such tools, regardless of the underlying algorithm and method. AI can aid product development immensely, through design automation utilising knowledge-based engineering and design optimisation as shown in the proposed framework. A natural continuation is to combine these strains of research by studying the application of learning-based methods to design automation and configuration in a mass customisation context to further improve the capabilities of the proposed framework.

5 CONCLUSION

This licentiate thesis is concluded by answering the research questions stated in section 1.2, based on the research presented in the thesis and the appended papers.

RQ1. What are the key characteristics to successful implementation of product configuration in mass customisation contexts?

In order to successfully implement PCS in a mass customisation context, it is of utmost importance to understand their position in the PDP, the level of customisation required, and the subsequent level of standardisation contra flexibility of its database. By connecting multiple PCS, each focusing on distinct development phases, a framework can be structured to aid throughout. Seamless translation of design data between the systems is essential in order to allow unimpeded communication between phases. Key to the success of a configuration framework is maintained flexibility, enabling the introduction of new products and solutions as well as organisational changes.

Configuration of CAD models can be achieved using High Level CAD templates (HLCT). The method provides crucial levels of freedom in developing a PCS, allowing for morphological and topological control of geometry, parametrically as well as context based. With all design information embedded in the template files themselves, a HLCT-based configurator remains maintainable. Identified characteristics essential to configuration for mass customisation are described in detail in section 3.3, and their impact discussed in section 4.1, based on the findings published in papers I-III.

RQ2. How can product configuration be extended from traditional product design to include phases such as sales and production preparation?

A framework aimed at integration between sales, design, and production phases of the PDP is described in chapter 3, as proposed in paper I. With the framework incorporating multiple configurators, integration between sales and conceptual design can be accomplished through one configurator utilising lightweight representations for rapid design iteration in dialogue with the customer and subsequent quotation. Blueprints of finalised conceptual designs are utilised by a second configurator based on HLCT to generate detailed, complete designs. Fully configured models contain

information for subsequent automatic generation of production data, thereby integrating design and production.

Integration with sales processes is further extended in paper II towards enterprise-wide optimisation with the aim of coordinating orders with production planning, see section 3.4. Preparation of production data is discussed further in paper III, as described in section 3.5, showcasing development of configuration frameworks including multiple production preparation techniques in an engineering educational setting.

RQ3. How can design automation and product configuration leverage artificial intelligence?

Through KBE and design automation, the proposed configuration framework for mass customisation of complex products builds on a foundation of AI. The inclusion of design optimisation allows for rapid design iteration and subsequent quotation in sales and conceptual design phases as well as generation of production data from detailed designs. In implementation of enterprise-wide optimisation, a configuration framework can be instrumental in elevating the PDP to further reduce costs through coordination of orders. As discussed in section 4.3, design automation and product configuration can further leverage artificial intelligence through implementation of learning-based methods utilising historic data. Examples identified through the literature review in paper IV include improvement of the current design optimisation process with surrogate models for simulation and automated recognition of customer requirements and translation thereof into design data. Furthermore, reinforcement learning may be of interest due to its self-sufficiency without relying on vast amounts of data and its rule-learning ability.

In continuation of this work, the merger of product configuration with recent advances in AI and visualisation will pave the way for a broader usage of configuration systems in the future of product development for mass customisation.

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Papers

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'People think of education as something that
they can finish.'

Isaac Asimov, 1988

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