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Design Automation for Additive Manufacturing

A Multi-Disciplinary Optimization Approach

Anton Wiberg

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¹Artomize (verb), the process of creating individualized art automatically. Can also be referred to as Customized Art, Automated Art, or Randomized Art.

ABSTRACT

Additive manufacturing (AM) is a group of manufacturing methods which have attracted rapidly increasing interest in academia and industry during the last years. AM's main benefits are manufacturing of complex shapes and small-scale manufacturing, without the additional cost of traditional manufacturing methods. Creating complex geometries that fully leverage the potential of AM requires time, knowledge, and design skills. Design for additive manufacturing (DfAM) is a vast area that includes methods and tools that aim to overcome the challenges of AM and support the development of new components and products.

Design automation and optimization are two terms often mentioned as potential methods to support the DfAM process. In a broad definition, design automation (DA) refers to reusable computer tools developed to aid the design engineering process. The general idea with DA is to create flexible design processes where different solutions can be explored without an increase in manual work. Together with methods for design optimization, DA has shown the potential to support the DfAM process.

This work focuses on how DA technologies can support the development of components manufactured by AM. By analyzing the current state of the art, today's DfAM process is mapped, and the potential for automation is explored. The work contributes to the field by presenting a holistic DA framework that bridges function, design, AM setup, and post-processing. A master model is used to span the different phases of the design process and utilize combined optimization of geometry and manufacturing setup. The proposed method is refined in an iterative process where details are solved, and computer tools supporting the process are developed. Application cases from the aerospace sector and the fluid power industry are used to evaluate and demonstrate the developed methods and computer support.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Additiv tillverkning (AM) är en samling av tillverkningsmetoder vilka intresset från akademi och industri ökat snabbt under de senaste åren. AM:s främsta fördelar är möjligheten att tillverka komplexa former samt tillverkning i få exemplar utan extra kostnad jämfört med traditionella tillverkningsmetoder. Att skapa komplexa geometrier som fullt ut tar tillvara på potentialen med AM är en utmaning som kräver både tid och kunskap. För att möta dessa utmaningar så fokuserar det breda forskningsområdet design för additiv tillverkning (DfAM) på att utveckla metoder och verktyg som stödjer utvecklingen av nya komponenter och produkter.

Två termer som ofta nämns för att kunna stödja DfAM-processen är designautomation och optimering. I en bred definition syftar design automation (DA) till att skapa återanvändbara datorverktyg som underlättar konstruktionsprocessen. Den generella idén med DA är att skapa flexibla konstruktionsprocesser där olika geometrier och lösningar kan utforskas utan ökat manuellt arbete.

Detta arbete fokuserar på att undersöka hur metoder kopplade till DA kan stödja utvecklingen av komponenter tillverkade av AM. I arbetet kartläggs existerande metoder och datorverktyg som stödjer DfAM-process och en framtida process som bygger på DA föreslås. Arbetet bidrar till fältet genom att presentation av ett holistiskt DA-ramverk som försöker inkludera hela konstruktions och tillverkningsprocessen från funktion till AM tillverkning och efterbearbetning. Ramverket består av ett flertal metoder och datorprogram som stödjer processen och som kan användas för att automatiskt skapa, utvärdera och optimera komponenter. Genom arbetet förfinas den föreslagna metoden i en iterativ process där detaljer löses och datorprogram som stödjer processen utvecklas. Applikationsfall från flyg och hydraulikindustrin används för att utvärdera, och demonstrera de utvecklade metoderna och datorprogrammen.

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Anton Wiberg
Linköping, 2021

APPENDED PAPERS

Paper I

Wiberg, A., Persson, J. A. and Ölvander, J. (2019) Design for Additive Manufacturing - A review of available design methods and software, *Rapid Prototyping Journal*, Vol. 25 No. 6, pp. 1080-1094. <https://doi.org/10.1108/RPJ-10-2018-0262>

Work distribution: Anton Wiberg performed the literature study, compiled the results, and wrote the paper. Johan Persson and Johan Ölvander supported the review process and provided feedback on the paper structure and content.

Paper II

Wiberg, A., Persson, J. A. and Ölvander, J. (2019) Design for Additive Manufacturing Using a Master Model Approach, in *Proceedings of the ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Volume 2A: 45th Design Automation Conference. Anaheim, California, USA. August 18–21, 2019. ASME. <https://doi.org/10.1115/DETC2019-97915>

Work distribution: Anton Wiberg developed the method and computer application, performed the design application, and wrote the paper. Johan Persson and Johan Ölvander provided feedback on the proposed method and the paper structure and content.

Paper III

Wiberg, A., Persson, J. A. and Ölvander, J. (2021) An optimisation framework for designs for Additive Manufacturing combining design, manufacturing, and post-processing, *Rapid Prototyping Journal*, Vol. 27 No. 11, pp. 90-105. <https://doi.org/10.1108/RPJ-02-2021-0041>

Work distribution: Anton Wiberg developed the method and computer application, performed the design application, and wrote the paper. Johan Persson and Johan Ölvander provided feedback on the proposed method, paper structure and content.

Paper IV

Wiberg, A., Ericson L., Persson, J. A. and Ölvander, J. (2021) Additive Manufacturing in fluid power with a novel application to hydraulic pump design, submitted to *Rapid Prototyping Journal*

Work distribution: Anton Wiberg performed the review, compiled the result, developed the fluid model, performed the re-design, and wrote the paper. Liselotte Ericson provided the case component, supported the re-design, and contributed to explaining the pump

function in the article. Johan Persson and Johan Ölvander provided feedback on the paper structure and content.

Paper V

Wiberg, A., Persson, J. A. and Ölvander, J. (2021) A Multi-Disciplinary Design Automation framework for Additive Manufacturing, in Manuscript.

Work distribution: Anton Wiberg developed the method and computer application, performed the design application, and wrote the paper. Johan Persson and Johan Ölvander provided feedback on the proposed method, paper structure and content.

The following papers constitute a part of the background but are not included in the thesis:

Paper VI

Wiberg, A., Persson, J. A. and Ölvander, J. (2018) An Optimization framework for Additive Manufacturing given Topology Optimization results, *Tools And Methods for Competitive Engineering - TMCE 2018 Proceedings*

Paper VII

Persson, J. A. and Wiberg, A. (2020) Using Boundary Condition and Topology Optimization to Design an Airplane Component, *AIAA Scitech 2020 Forum*.

Paper VIII

Papageorgiou, A., Wiberg, A., Persson, J. A. (2021) Introducing Multidisciplinary Design Optimization to Graduate level Engineering Students, *Proceedings of the Design Society*, 1, 1917-1926. doi:10.1017/pds.2021.453

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INTRODUCTION

Engineering design and product development are complex processes with increasing demand for efficiency, functionality, sustainability, and innovation. The digital age has dramatically influenced the manufacturing industry, where computers control everything from robots to mills. A new era in the manufacturing industry began during the 1980s when several patents focusing on manufacturing by selectively adding material in a systematized way were filed. The technology has been referred to by different names during the years, such as 3D printing, rapid prototyping, and rapid manufacturing. In 2013, the international standard organizations ISO and ASTM came with the first standard, and stated that the term additive manufacturing (AM) should be used to describe the action of "*joining materials to make parts from 3D model data, usually layer upon layer*" (ISO/ASTM, 2017). During the last decades, the development of AM technologies has resulted in the development of several variants of the technique, many new materials that are possible to process, higher quality of the manufactured parts, and an increased market of inexpensive machines.

There are three potential advantages of using AM compared to other manufacturing techniques: the possibility of creating an individualized design without adding cost; the possibility of creating complex structures with integrated functionality; and the possibility to create lighter structures. All these advantages put a high demand on the design process, which has led to the introduction of the design for additive manufacturing (DfAM) field.

A way to meet the challenges of the future is design automation (DA). DA can be defined as the development of reusable design engineering support. The focus is on computerized automation of tasks that are directly or indirectly related to the design process (Cederfeldt and Elgh, 2005). DA includes a variety of methods and applications, with a common goal to increase efficiency and reduce the risk of errors (Rigger and Vosgien, 2018). Focus is often on automation of repetitive and non-creational tasks to free up time for the design engineer (Verhagen et al., 2012).

1.1. Motivation

While AM has a vast potential to revolutionize the industry, the manufacturing process puts high demands on design engineers. AM reduces the complexity of traditional manufacturing and part assembly, as a complete product could be manufactured in "one go." Hence, as the manufacturing process is more automated, the design process will become the bottleneck. In practice, this is not totally true, as post-processing is always required, and there are still many restrictions regarding AM. Simpson (2017) claims that today's design software and workflows do not harmonize with the types of challenges faced during the DfAM process. Therefore, this work explores the possibility of integrating DfAM with DA to fully leverage the AM possibilities.

In this context, the application of DA can be referred to as computational methods and tools which aid the processes of overcoming the so-called design paradox, presented in Figure 1. While the design freedom is extensive at the beginning of a project and diminishes as the project progresses, the knowledge of the product is low and increases over time. In this case, the goal with DA is to increase the possibility of making changes to the design later in the process (increasing design freedom) and expanding the knowledge early in the design process. In an AM case, one would want to solve the connection between design and manufacturing where the design can be adapted to an AM setup, or the AM setup can be adapted to a design. As Boothroyd (1994) describes, an ideal design process should simultaneously design the component and the manufacturing setup to optimize them both.

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

1.2. Thesis Aim

The overall aim of this work is to analyze and improve the DfAM processes with the goal of creating better products at a faster pace. The work presents a holistic overview of the DfAM processes, including existing design automation and optimization methods.

More specifically, the work aims to advance the current knowledge within DfAM by developing methods and computer support based on DA techniques.

To achieve the aim of the thesis, four main goals of the research will be addressed:

1. Identify state of the art in the DfAM process, trends related to DA and design optimization in the DfAM process, and potential gaps.
2. Develop DA methods that support the DfAM process.
3. Demonstrate computer systems that utilize DA to support the DfAM process.
4. Evaluate the developed methods and computer systems based on gains in the DfAM process.

1.3. Thesis Scope

Based on the research goals, one can state that the characteristic of the work is explorative with a broad scope. The work is performed at the intersection between DfAM and DA. Since the goal is to identify potential gaps in the DfAM process and show methodological and computer solutions that support the process, a large part of the work's contribution lies in bridging and adapting other people's work and ideas to a DA for AM context.

The work utilizes several methods from the engineering design and DA fields, and an overview of these is presented in Chapter 3. From engineering design, methods such as functional modeling (Hubka and Eder, 1988; Levandowski et al., 2016) and function simulation (Ulrich and Eppinger, 2012), see section 3.1. are employed. From the DA field, techniques such as knowledge-based engineering (Chapman and Pinfold, 1999; Rocca, 2012), product configuration systems (Hvam et al., 2008), object-oriented programming (Hopgood, 2001), parametric CAD modeling (Amadori et al., 2012), extended design structure matrix (Lambe and Martins, 2012), and multi-disciplinary design optimization (MDO) (Martins and Ning, 2021), are utilized during the development of the holistic DA framework presented in the thesis.

Methods related to AM and DfAM utilized in the thesis are presented in Chapter 4. Information pertaining to AM processing and materials, such as geometrical design rules, material properties, post-processing, and topology optimization for AM, is applied in the framework, but no new development in these areas are performed within the thesis. Methods are used and adapted to fit into a holistic MDO framework for DfAM including, adaption of AM design rules during geometry creation (Biedermann and Meboldt, 2020), design rule checks (Mani et al., 2017; Rudolph and Emmelmann, 2017), and ontologies for AM (Liu and Rosen, 2010).

Related areas which are not yet considered in this work but discussed for integration in the future (see Chapter 7 and 8) are design heuristics (Blösch-Paidosh and Shea, 2019; Lindwall and Törlind, 2018), simulation of the AM process (Bikas et al., 2016), design

uncertainties (Borgue, 2021), and qualification aspects of introducing AM in industry (Dordlofva, 2020a).

The methods and tools proposed in this work are created to be generic in terms of material, AM process, and application area. When selecting the application cases for evaluating the methods and framework, a delimitation is mechanical engineering components directly manufactured by metal AM (e.g. not manufacturing of tools or molds) using the technology powder bed usion (see section 4.1.).

1.4. Thesis Outline

This thesis is divided into eight chapters: *Introduction; Methodology; Design Automation Technologies; Design for Additive Manufacturing; Design Automation for Additive Manufacturing; Application Cases; Discussion; Conclusions*, see Figure 2. Chapter 2 explains the method applied with insights into research and development methodologies and how they are used in this work. Chapter 3 and 4 present background theory, which lays the foundation of the performed work. In Chapter 3, theory coupled with DA is presented, whereas Chapter 4 presents the state of the art in DfAM with existing design methods and theory associated with a proposed design process. Chapter 5 presents the proposed DA framework developed within this work. Chapter 6 presents application cases where different parts of the framework are demonstrated in design studies. In Chapter 7, the strengths and weaknesses of the work are discussed in both an academic and industrial setting. Finally, the thesis is concluded in Chapter 8, where the work is reflected upon based on the four goals presented in 1.2.

Figure 2: Outline of this thesis.

METHODOLOGY

The purpose of this chapter is to describe the methodologies applied during the work on the thesis. The chapter starts with a description of some generic methods for design research in section 2.1. Based on the presented methods, section 2.2. describes how the methods are applied in this work.

2.1. Research Methods

Basic scientific research's primary aim is to build new fundamental knowledge, while applied research, such as engineering design research, besides creating new knowledge, also is oriented towards solving practical problems (Eckert et al., 2003). Drexler (2013) uses an information flow model to distinguish between scientific inquiry and engineering design. As described in Figure 3, in a scientific inquiry, information flow from a physical system via measurements and data towards a general theory. At the same time, in engineering design, the starting point is ideally an abstract model, which through concretization is transformed into a useful product.

Figure 3: Comparison between science and engineering design, adapted from (Drexler, 2013).

Successful research should always seek and identify new knowledge (Cross, 2012). According to Hubka and Eder (1996) knowledge in engineering design can be divided into two scales, one from object to process knowledge and the other from domain to general theory (see Figure 4). To successfully span these two dimensions, scientific inquiry is typically combined with engineering design practice. In scientific inquiry, the object of study could be the engineering design process itself. Frayling (1993) describes three types of scientific inquires for engineering design. Research into design, research through design, and research for design. Research into design, is performed by

Figure 4: Different kinds of knowledge in engineering design, according to Hubka and Eder (1996).

observation of documented engineering design processes. An actual design process is performed in research through design, and self-observation of the process is turned into research. Research for design focuses on developing design methods and creating tools that aid the design process (Hubka and Eder, 1996). In the two former approaches, the scientific inquiry approach could be applied to the design process itself, with varied degree of researcher involvement.

In the separate Papers and phases of this work, different approaches are used. As described in section 2.2., the general framework developed is employed in two application cases from diverse industries. The framework development is performed in research for design inquiries where computer tools and methods supporting the design process are developed. The application cases are examples of research through design. During these processes, the goal is to transform object and domain-specific knowledge (upper left corner in Figure 4) to general theory of the design processes. This is performed by tracking the outcome of the application cases to how the design process is implemented. This process can be compared to the information flow presented in Figure 3, where the application cases are examples of engineering design processes where design concepts are transformed into useful products.

2.1.1. General Design Research Methods

A research method often used in engineering design is the design research methodology (DRM) (Blessing and Chakrabarti, 2009), that consists of four steps performed iteratively, as illustrated in Figure 5. The four steps in DRM are:

- Research clarification (RC): Build evidence or at least find indications that the research field is valid and the research goal is specified. This could for example be accomplished by literature review and field observations.
- Description study I (DS-I): Identify the main challenges in the research and determine which factors the continuing research should focus on.
- Prescriptive study (PS): Development of support that will aid future work and help to overcome the gap identified in DS-I. The developed support could be in the form of software, algorithms, or other tools that aid the design process.
- Description study II (DS-II): Evaluation of the developed support in a realistic environment including comparison to the research goal.

Figure 5: The design research methodology, adapted from Blessing and Chakrabarti (2009).

Industry-as-laboratory is a concept founded in software engineering research, with the goal to perform research in close collaboration with industrial projects (Potts, 1993). Central in the approach is a direct inspiration of industrial applications where the research problem comes from understanding the application environment. This benefits from a detailed awareness of the challenges, direct feedback on the case study, and a clear view of future possibilities. Muller (2018) introduced the industry-as-laboratory concept to the engineering design field. In Muller's case, design engineering problems are used as inspiration and case studies during the development and evaluation of new design methods (see Figure 6).

Figure 6: The industry-as-laboratory research approach, inspired by (Potts, 1993).

2.1.2. Literature Studies

A method to investigate state of the art in a research field is literature reviews. Two types of literature reviews are breadth-first and depth-first. Breadth-first is what could be referred to as the traditional method where a structured process is used to define search strings, and the result is formally reviewed and filtered down to find relevant publications (EBSE, 2007). In a depth-first approach, methods such as snowballing are instead used to find relevant literature based on one or more base publications (Wohlin, 2014).

2.1.3. Research Validation

Since the result of a design process is influenced by many factors, repetition and validation of a proposed design process are complex, as there seldom exists a control group to compare with. For this reason, the evaluation of design research becomes intricate, and traditional validation methods cannot be used. Buur (1990) instead proposes that design research can be evaluated through verification by acceptance or logical verification. Verification by acceptance is performed by investigation if experienced designers and research peers accept the proposed theory, methods, and models. Logical verification is performed by analysis of the proposed method and checks if it fulfills specific points such as:

- The proposed method should be complete and consistent.
- The proposed method should be built on well-established methods and theory.
- The proposed method should be able to explain the outcome from case studies.

Olesen (1992) extends the criteria for evaluation with the factors applicability and novelty value. Applicability determines what the result contributes with, compared to if the method or tool would not have been used. The novelty factor assesses to what degree the method is novel enough to be seen as a contribution.

2.2. Applied Methodology

The work in this thesis combines the methods presented in section 2.1. Similar to the DRM, the research is performed in four stages where the first two focus on setting the scope of the work and propose new approaches. Input for these stages are challenges defined by industry, together with analysis of state of the art. Where input is gathered from literature reviews and workshops with industrial partners. In the two following phases, computer support is developed and evaluated. During this process, application cases from the industry are used in real-world product development processes. Best practice methods and rules of thumb are incorporated in the development. Figure 7 shows the applied methodology with the four DRM steps in the center, and above in which stages industry and academia are involved, and at the bottom the output from these steps.

Overall, the work can be divided into theory, method development, tools development, and application. Theory refers to the collection and usage of current research. Method development is used to develop generic methodologies, while tools development implements the methods in computer systems to verify the methods' relevance. In the application, cases from the industry are used to put the methods and tools into practice.

Figure 7: The applied research methodology combines the DRM and industry-as-laboratory methods.

The work has been performed within two research projects, AddMan and AMHY (see Table 1). Both projects involved several partners from academia and industry. In both cases, the industrial partners were engaged as sources of inspiration for setting up the project's goals, demands, and restrictions, and for evaluating the proposed methods. Application cases used to demonstrate and evaluate the developed methods have also been taken from the industrial partners.

Table 1: Research projects.

Project	Acronym	Year
Innovative Re-design and Validation of Complex Airframe Structural Components Formed by Additive Manufacturing for Weight and Cost Reduction	AddMan	2017 - 2020
Additive Manufacturing for the hydraulics industry - possible paths to new value-creating design	AMHY	2020-2021

A significant part of the general AM theory is collected within Paper I, which presents a systematic literature review where state of the art in DfAM is mapped out, and a research gap is identified. The literature study combines a systematic breadth-first approach with snowballing to identify potentially missed literature. As shown in Figure 7, the literature review and needs from the industry are used to formulate a hypothesis in the form of a new design approach.

Papers II, III, and V refine the approach from Paper I and describe methods that enable the realization of the design process. During this work, research for design is used to develop computer tools that build on the method and aid the implementation of a computer framework. The application cases from the industry are used in research through design processes where products are designed with the composed framework. The model presented by Drexler (2013) (see Figure 3) is used. More specifically, a normal engineering design process is followed by a scientific inquiry where the methods are evaluated based on the performed design process and its result.

Verification by acceptance is performed by sharing the result with the project consortium in the form of papers and seminars. The publications are published in peer-reviewed journals and conferences, a type of verification on its own. Logical verification is

also performed within the papers where the proposed methods are built on well-known methods. Finally, the results are discussed from a consistency point of view and, in some cases, compared to other design alternatives.

In Paper IV, no new method is presented; instead, the paper reviews a novel use of AM and provides an application case where parts of the methods are applied. The work of the five papers can be divided into theory, method development, tool development, and applications. Figure 8 illustrates how each of the appended papers contributes to the thesis goals, which parts of the DRM processes are considered, and if the paper focuses on existing theory, method development, tools development, or application. It also describes which research project the paper belongs to, which research goal the work contributes to, and how it is coupled to the DRM process.

Figure 8: Overview of the contributions of the appended papers.

DESIGN AUTOMATION TECHNOLOGIES

As stated in the Introduction, DA can be defined as developing reusable computer functions that support the design process (Cederfeldt and Elgh, 2005). This chapter first introduces some general concepts of the engineering design process (section 3.1.), followed by a presentation of the methods used to develop DA support in the thesis.

3.1. Engineering Design

Engineering design is the process of defining a physical form of a product from a set of customer needs and requirements. This process can be divided into four phases: conceptual-, preliminary-, detailed- design, and finally, production (Ulrich and Eppinger, 2012). During the design process, the product knowledge successively increases. On the other hand, the cost of making changes increases, thereby decreasing the possibility of changing the design or manufacturing (Ullman, 2010) (see Figure 1).

Within the conceptual phase of the engineering design process, the identified customer requirements are transformed into conceptual solutions. A commonly used method for this is to divide the product requirements into functional requirements. Based on the functional requirements, conceptual generation and exploration can be used to find solutions for each function individually (Hubka and Eder, 1988). In this process, a structural decomposition, so-called functional modeling, can be used to identify a product's function (Ullman, 2010). Enhanced function-means modeling (EF-M) is a further development used to connect solutions of functions with their functional requirements (Levandowski et al., 2014; Malmqvist, 1997). The functional representation can be saved in an object-oriented programming (see section 3.2.1.) system by feature-based modeling. However, there is no consensus on what a product feature is or how it should be used, which can hinder data exchange in the process (Romero et al., 2019). Further in the product development process, a synthesis process can be used to combine solutions into product concepts (Chakrabarti et al., 2011).

The preliminary, detailed, and manufacturing phases of the design processes are today dominated by computer-aided methods. These include computer-aided design (CAD)

tools for geometrical creation, computer-aided engineering (CAE) software for analysis of a design, and computer-aided manufacturing (CAM) methods used for production preparation and simulation (Ulrich and Eppinger, 2012). CAE methods can be used to evaluate many different design characteristics but are often divided into 1-, 2-, or 3D simulations depending on how the geometry is handled. In 1D simulations, geometry is either neglected or simplified to only specific parameters; 2D and 3D simulations are based on specific geometry, often extracted from a CAD representation.

3.2. Knowledge-Based Engineering

A primary key to realizing DA is utilizing knowledge-based systems, software applications designed for intelligent knowledge capture and use. As shown in Figure 9, knowledge-based systems consist of a knowledge base that is used to save information, an inference engine that processes the knowledge, and a user interface for capturing input and presentation of responses (Elgh, 2007). By separating the knowledge base and the inference engine, knowledge can be updated and added. The inference engine in a computer system can be rule-based, object-oriented, or based on intelligent agents (Hopgood, 2001).

Figure 9: The basic structure of a knowledge-based system.

The application of knowledge-based systems in engineering design is often referred to as knowledge-based engineering (KBE) (Chapman and Pinfold, 1999). According to some (Kuhn et al., 2012; Rocca, 2012a), KBE is a concept that connects knowledge-based systems and CAD, whereas others (Stokes, 2001) have a more general view where everything connected to knowledge capturing and reuse in the engineering design process is included. Rigger et al. (2018) divide DA methods into input and output of the system, the goals, and which methods are used to perform actions within the system. The inputs can be a direct variable, other input values, a set of requirements, some kind of functional or product architecture. Output can be manufacturing plans, solid models, finite-element analysis (FEA) meshes, or others (La Rocca, 2012).

Creating a KBE system is done in three steps: knowledge capturing, formalization, and representation (Colombo et al., 2014). In the knowledge capturing phase, information that supports the KBE system is collected by domain experts. In the formalization step, the knowledge is organized in a structured way. In the engineering representation, the knowledge is represented in one of the ways described for general knowledge systems (rules, objects, or agents) but with the addition of geometrical knowledge representation (Colombo et al., 2014).

An extension of the use of interfaces in knowledge-based systems is configurators. Configurator systems are IT systems that support sales, product design, and manufacturing (Hvam et al., 2008). An essential aspect of configurator systems is linking customer and commercial aspects with the technical (Forza and Salvador, 2008). Product configurator systems have been mentioned as a central component to accomplish mass customization (Hvam et al., 2008).

3.2.1. Object-Oriented Programming

The two standard ways of structuring programming code today are functions and classes. While functions are methods that receive inputs, perform a task, and deliver an output, classes are objective-oriented programming language templates that store information in an object. A class consists of a set of attributes and functions. The attributes describe the state of an instance of the class (referred to as object). The class functions are different ways to manipulate the object (Hopgood, 2001).

Compared to standard object-oriented programming, a KBE system typically has a more formal definition of the attributes and functions organization. Different product variants are defined by the combination of objects and attribute values. A KBE framework often directly connects the objects and geometrical CAD features (La Rocca, 2012). The knowledge objects in a KBE system should be autonomous, performing their task with only some initial input (Johansson, 2011).

XML (extensible markup language) stores data in a readable format for both humans and computers. The basic structure of XML is hierarchical and based on elements that can contain child elements. Since XML is consistently organized where elements are named, defined, and tagged, the content is easily reusable and can be read by other software (Amiano et al., 2006).

3.3. Geometry in Design Automation

A central component in DA is the creation and modification of the geometry. A computer can represent geometries in several ways with different pros and cons. A way to separate geometrical representation is into the following three categories (see Figure 10):

- Feature-based CAD
- Volume mesh
- Boundary representation

All three categories contain different sub-methods for incorporating geometry. In this categorization, feature-based CAD is built up by form features such as extrudes, holes, etc. These can be created by geometric elements such as circles, sketches, curves, points, and others. A volume mesh is built up by 3D elements (such as tetrahedrons and cubes)

which represent material. Boundary representation only includes the surface that creates the boundary between material and no material. This can be performed by mesh elements or by curves. Traditional CAD systems are often based on features but can combine this with boundary representation by surface modeling or other methods. Figure 10 compares the three approaches, where the revolution of a circle creates the feature-based geometry, the volume mesh is built up by voxels, and triangular surfaces make the boundary representation.

Figure 10: Comparison of methods for geometry representation.

During this work, the focus has been on using methods for feature-based CAD for geometry representation. The main advantages of using this method are the extensive support from traditional CAD software, easy creation of relations and parameters, the possibility of connecting features with object-oriented programming directly, and the possibility of creating product configurations. Disadvantages worth mentioning are the difficulty of making geometry changes not planned before building the model and the risk of unstable models (Salomons et al., 1993; Shahin, 2008).

3.3.1. Feature-Based CAD

Feature-based CAD software can, in addition to geometry, capture knowledge in seven different ways (user-defined attributes, feature names, parameters, annotations, programmed features, and additional geometry) (Heikkinen et al., 2018). User-defined attributes, feature names, annotations, and additional geometries add supplementary information to the model, which can be helpful for external scripts or functions that handle the geometry. Programmed features can be used to build rules or relations in the model that reacts to internal measurement or parameter input. Finally, parameters utilize a straightforward modification of the geometry. Eigner et al. (2010) show how a CAD file can be combined with an XML file to save other types of information and apply it to create different geometries dependent on its application.

Geometry modifications in a feature-based CAD system can be divided into morphological and topological. Morphological changes modify the size or shape of a feature. Topological changes refer to the creation or removal of a geometrical feature. High-level CAD templates (HICt) (Amadori et al., 2012) refer to geometrical features stored in templates and instantiated in different contexts. A CAD template can, in addition to geometrical elements, contain parameters, rules, or any of the other knowledge mentioned above.

3.4. Design Optimization

Most of the DA methods presented in this chapter are enablers to create and evaluate products automatically. Design optimization is used to find designs that best fit a set of requirements. A general optimization problem consists of an objective function (f), one set of inequality constraints (g), and one set of equality constraints (h). All of these are affected by changes of a group of variables ($\mathbf{x}$) where the upper and lower variable limits are set for each variable (Sobieszczanski-Sobieski et al., 2015), see Equation 1. In a design optimization problem, the variables ($\mathbf{x}$) typically are coupled to the geometry. These can, however, be combined with other types of variables such as material and manufacturing settings.

$$\begin{aligned}
 & \min_{\mathbf{x}} f(\mathbf{x}) \\
 & \text{subject to:} \\
 & g_j(\mathbf{x}) \leq 0, \quad j = 1 \dots m \\
 & h_k(\mathbf{x}) = 0, \quad k = 1 \dots p \\
 & x_i^{lower} \leq x_i \leq x_i^{upper}
 \end{aligned} \tag{1}$$

Optimization problems can be classified based on their characteristics. This includes single or multi-hierarchical, single or multi-objective, convex or non-convex, linear or non-linear objectives and constraints, and if the variables are continuous or discrete (Papalambros and Wilde, 2000).

3.4.1. Optimization Algorithms

Different kinds of optimization algorithms can be used to solve optimization problem as the one presented in Equation 1. Two types of methods are derivative and non-derivative methods (Andersson, 2000). As the name implies, derivative methods calculate the derivatives of the objective function with respect to the design variables and change the variables in the direction which minimizes the objective function the most. Derivative algorithms are typically fast, and can prove optimality of the found result (e.g. if the problem is convex, the derivatives equal zero, and second-order partial derivatives positive in case of a minimal point). However, the disadvantages are that it is necessary to

calculate the derivatives, which may be difficult for complex problems, and the algorithm tends to get stuck in local optima if the problem is non-convex. There are solutions to overcome these problems by reformulating the optimization, but this can be a complex task (Martins and Ning, 2021).

Non-derivative methods are methods that search for optimal solutions without the calculation of derivatives. This results in the methods not proving optimality of the found solutions, making some claim that they are not optimization algorithms but instead heuristics. The considerable advantage of non-derivative methods is the simplicity of handling broad optimization problems, including multi-objective optimization (Beasley et al., 1993).

Genetic algorithms (GA) are optimization algorithms that aim to imitate evolution in nature by representing the design variables as genetic strings. GA works by creating a set of different designs (a generation). The designs are evaluated and based on the objective function value, the best designs are combined (using cross-over), and a new generation of designs is created. These algorithms have shown to be very effective to apply to complex multi-objective and multi-disciplinary problems. The disadvantage is that they are relatively computationally expensive (Goldberg, 1989).

3.4.2. Structural Optimization

Structural optimization refers to the subfield of design optimization where geometrical structures are optimized. Christensen and Klarbring (2009) divide the field into the categories size-, shape-, and topology- optimization. This categorization can be coupled to the way of handling the geometry (see section 3.3.), where size optimization is coupled to a feature-based geometry, and feature attributes are used as variables. In shape optimization, the shape of the component boundary is altered. In topology optimization (TO), a volume meshed design space is used as a start, and the density of each element is changed.

Where size and shape optimizations require a start geometry, TO has the advantage of creating a design just from a meshed design space. The result from a TO comes in the form of a density map, which can be transferred into a boundary representation (Christensen and Klarbring, 2009). A challenge with TO is how the result should be used, since it is difficult to manufacture and time-consuming to remodel for adaption to manufacturing (Zegard and Paulino, 2016).

3.4.3. Multi-Disciplinary Design Optimization

Multi-disciplinary design optimization (MDO) refers to the use of multiple design and simulation disciplines in design optimization (Simpson and Martins, 2011). MDO enables systematic exploration and optimization of design problems that consist of multiple variables and phenomena that affect each other (Vandenbrande et al., 2006). The

creation of an MDO framework to solve a complex engineering problem includes several tasks, such as the identification of necessary disciplines to incorporate, in which order the disciplines should be calculated, development/adaption of CAE models representing the disciplines, and technical implementation of the models into a framework (Martins and Ning, 2021). When such a framework is created, it can be used for multi-disciplinary analysis (MDA) to analyze one design or find better solutions by optimization.

MDO architecture or problem composition describes in which order disciplines are calculated in the framework (Martins and Lambe, 2013). An architecture can either be single- (monolithic) or multi-level (distributed). Single-level frameworks calculate the included CAE models in consecutive order. At the same time, distributed architectures split the problem into smaller problems which can be solved many times before continuing to the next. The order in which the disciplines are assessed can be described by an extended design structure matrix (XDSM) (Lambe and Martins, 2012).

In the forthcoming applications, GA are used to solve multi-objective and multi-disciplinary optimization problems, where XDSMs are used to describe the developed frameworks.

DESIGN FOR ADDITIVE MANUFACTURING

This chapter introduces techniques for AM, materials that the techniques can manufacture, and some advantages and disadvantages with the methods. The chapter also presents current knowledge in DfAM and introduces specific DA and optimization research adapted for AM. The chapter is, to a large extent, built on the literature review reported in Paper I.

4.1. Additive Manufacturing

ISO and ASTM define AM as manufacturing where parts are created by successively adding material, often in a layer-by-layer approach (ISO/ASTM, 2017). AM should not be seen as one manufacturing process but rather a collection of seven process categories which can also be divided into several manufacturing techniques. The seven AM categories are vat photopolymerization, material extrusion, material jetting, binder jetting, powder bed fusion, direct energy deposition, and sheet lamination (Gao et al., 2015). In vat photopolymerization, liquids, resins, or photopolymers are solidified in a photopolymerization reaction. The material extrusion process works by pressuring semi-solid material through a nozzle. The material must harden while keeping the shape from the nozzle. Material jetting can be seen as a combination of 2D inkjet printing, photopolymerization, and material extrusion. Machine setup and movement are similar to material extrusion, but the material is directly fabricated using photopolymerization. Binder jetting is related, but a binder is applied to form objects. In powder bed fusion (PBF), metal, plastic, or ceramic powder is distributed in thin layers and manufactured by an energy source during a sintering or melting process. Direct energy deposition works by applying powder or wire material on a component or platform. The material is fabricated by a laser or electron beam as in PBF. Lastly, in sheet lamination, sheets of materials are added and cut into cross-sections of the desired geometry (Gibson et al., 2010). Figure 11 presents an overview of which materials the methods can manufacture and some pros and cons connected with them.

AM CATEGORY							
MATERIALS	Vat Photo-polymerization	Material Extrusion	Material Jetting	Binder Jetting	Powder Bed Fusion	Direct Energy Deposition	Sheet Lamination
PROS/CONS	Photopolymers, Ceramics +High building speed +Good part resolution -Overcuring -High cost	Thermoplastics, Ceramic slurries, Metal pastes +Inexpensive +Multi-material printing - Limited resolution - Poor surface finish	Photopolymer, Wax +Multi-material printing +High surface finish - Low-strength material	Polymer, Metal, Ceramic powder +Full color +Wide material selection - Require infiltration during post-processing - High porosities	Polymer, Metal, Ceramic powder +High Accuracy +Fully dense parts +Good material properties - Powder handling & recycling - Support & anchor structure	Metal powder or wire +Repair on parts +Graded material printing - Bad resolution - Expensive	Plastic film, Metal sheet, Ceramic tape +High surface finish +Low cost - Waste material

Figure 11: Introduction to the pros and cons of the seven AM categories.

4.2. Design for Additive Manufacturing

DfAM originates from design for manufacturing (DFM), which is the design of a product where manufacturing, testing, assembly, service, repair, and cost are optimized without compromising safety, time-to-market, functionality, or styling (Boothroyd, 1994). DfAM includes research regarding methods, tools, and information that can aid different parts of the AM design and manufacturing process (Gao et al., 2015). Several attempts of categorizing the work related to DfAM exist (Kumke et al., 2016; Laverne et al., 2014; Rosen, 2014; Wiberg et al., 2019; Yang and Zhao, 2015). This work uses four categories: selection and ideation, design and optimization, AM preparation and verification, and post-process preparation and verification. Compared to a traditional product development process, a difference is a need for tighter integration between product design and process development. This is as a result of the manufacturing processes where design has a significant influence on the manufacturing process, but the manufacturing process also has an extensive effect on part quality. This requires tighter integration between detail design and production. Figure 12 shows the four DfAM steps together with the product development phases.

Figure 12: Four steps in DfAM.

4.2.1. Component Selection and Ideation

During the component selection and ideation step, the focus lies on finding suitable components to be manufactured by AM, defining the system boundaries between parts, and creating initial design concepts. Traditionally, AM has been used for the manufacturing of prototypes. However, today AM is used for prototyping as well as for end-products and the creation of tools and molds (Klahn et al., 2015). Using AM instead of traditional manufacturing methods creates the potential to develop parts with integrated functionality, leading to a reduction in the part count. Benefits are the reduced assembly operation and the potential to reduce unnecessary part space and mass. Integrated functionality could also be expressed as complex internal channels or other complex shapes. Weight optimization is something that complex shapes can also achieve. Another possibility with using AM is to create customized and small-series designs (Klahn et al., 2014).

Concept development and ideation in the early DfAM process can be aided by design heuristics (Blösch-Paidosh and Shea, 2019; Lindwall and Törlind, 2018). A similar method for increasing innovation in the AM concept development is design principles (Perez et al., 2019), which include manufacturing variables early in the process (Mani et al., 2017).

Some proposed activities for this step in the DfAM process are presented in Figure 13.

Figure 13: Activities with the component selection and ideation step, further developed from Paper I.

4.2.2. Component Design and Optimization

The relatively small manufacturing constraints make it attractive to use optimization methods during the design of AM components. One of the trends in DfAM is the use of TO, which is attractive since basic TO directly achieves weight optimization, which in addition to lowering the mass in many cases also reduces manufacturing time and cost. Despite the free form possibilities with AM, design rules such as overhang constraints still need to be considered in the TO process (Zegard and Paulino, 2016). Filters that respect AM design rules in TO are constantly developed and include avoiding overhangs, anisotropic material behavior, and others (Liu, Gaynor, et al., 2018). While direct manufacturing of TO results is sometimes possible, it can still be problematic if new information which needs to be considered appears or if compensation for manufacturing or post-processing is necessary.

Verification of manufacturing during the design stage can be performed by checking geometrical rules (Adam and Zimmer, 2015). Rules can be used proactively to create

suitable solutions, or they can be used to check the manufacturability of an already existing design. A proactive approach where overhang in internal channels is avoided by automatical adaptation of the cross-section is shown by Biedermann et al. (2021).

Activities within the design step of the DfAM process are presented in Figure 14.

Figure 14: Proposed activities in the design step, further developed from Paper I.

4.2.3. AM Preparation and Verification

Gibson et al. (2015) describe preparing and performing AM as an eight-stage procedure, from CAD model to application. The process contains both digital steps, such as file conversions and setup of the AM process, and physical steps, with removing of the component from the AM machine and post-processing. In the AM preparation and verification step of DfAM the geometry needs to be converted to a suitable format and read into AM preparation software, where the manufacturing is prepared. In this process, support material is created, AM preparation is performed, and build time and cost are evaluated.

In addition, the manufacturability needs to be verified. As described in section 4.2.2., verification of AM can be performed on an existing design by geometrical rules. This process can be automated, where design rules are formulated as functions that can predict manufacturability (Mani et al., 2017; Rudolph and Emmelmann, 2017). Another method to verify manufacturability is by utilizing computational simulation. This method is more general and can predict failures and deformations of prints (Bikas et al., 2016). On the other hand, the simulation is computationally expensive and requires expensive software licenses. In most cases, they are therefore used late in the design process to check a design before manufacturing or to investigate why a manufacturing attempt failed.

Proposed activities for AM setup and verification are presented in Figure 15.

Figure 15: Activities for AM setup and verification, further developed from Paper I.

4.2.4. Post-Process Preparation and Verification

Depending on the AM process, material, and application, post-processing of AM components may be necessary. The most apparent reason for the usage of post-processing is removing the part from a build plate, removing surrounding powder (PBF methods), removing support material, and ensuring tolerances of geometrical features (Schnabel et al., 2017).

Another application for the post-processing of AM components is the improvement of material properties (Kahlin et al., 2020). The tensile properties in AM materials, in terms of yield strength (YS) and ultimate tensile strength (UTS), are comparable to components manufactured using conventional methods (Lewandowski and Seifi, 2016). However, the fatigue properties are generally worse due to rough surfaces and internal defects (Kahlin et al., 2017). The fatigue life can be increased by utilizing post-processing methods, such as hot-isostatic pressuring, laser-polishing, shot peening, finishing, and centrifugal finishing (Kahlin et al., 2020).

The post-processing processes utilized need preparation, both in the manufacturing step setup and the geometry's compensation before the AM process starts.

As shown in Figure 16, the post-processing setup includes activities for selecting processes, designing the processes, and preparing the manufacturing model to compensate for the operations.

Figure 16: Activities for setup and design of the post-processing operations, further developed from Paper I.

4.3. Design Automation and Optimization in DfAM

A barrier to creating complex designs that fully leverage the opportunities with AM are the existing computer software and design tools (Guo and Leu, 2013; Thompson et al., 2016; Yang and Zhao, 2015). CAD software is often built upon low-level geometric primitives, which makes it time-consuming and tricky to create complex designs (Biedermann and Meboldt, 2020; Riesenfeld et al., 2015). Research and industrial implementations that utilize different kinds of DA and optimization methods for support of the DfAM processes have been presented. As described in section 4.2.2., a popular approach is TO. However, applying TO during a complete DfAM procedure is still challenging, and reverse engineering is often required (Liu, Li, et al., 2018; Nana et al., 2017).

Alternative methods of applying DA in the DfAM process include building setting optimization during the design process (Hu et al., 2015; Zwier and Wits, 2016; Asadollahi-Yazdi et al., 2019; Jiang et al., 2019), automatic AM design rules assessment (Ranjan et al., 2017; Rudolph and Emmelmann, 2017), automatic generation of geometrical features which consider AM design rules (Biedermann et al., 2021; Biedermann and Meboldt, 2020), ontologies for AM settings and parameters (Kim et al., 2019), and optimization of AM processes parameters (Wang et al., 2019). In addition, a large amount of commercial software can support different parts of the DfAM process (Nieto and Sánchez, 2021).

Most methods and software utilizing DA and optimization in the DfAM processes are limited to one discipline or parts of the design process. A challenge is that most decisions are coupled, and a change in, for example, post-processing can significantly influence the optimal geometry or AM setup (and vice versa) (Gao et al., 2015). The challenge in the design process is that it is complicated, costly, and time-consuming to bridge several types of software and models. This creates a risk that the designer will skip design steps that can make the design better.

In Paper I, it is proposed to utilize DA and MDO techniques to create an integrated design and manufacturing framework. The framework is proposed to be holistic by including geometry updates, functional verification, manufacturing and post-processing setup, and verification in an automatic context. Figure 17 presents an updated version of the DA framework from Paper I. Activities from the component selection and ideation step are performed as proposed within this chapter, but the design, optimization, preparation, and verification activities are automated.

Figure 17. Proposal of an integrated DA framework for DfAM, first presented in Paper I.

Recent work focused on a holistic DfAM process include (Vaneker et al., 2020) which proposes a similar framework that include design, process selection, and post-processing. The work discusses different design and optimization methods but does not present a coherent DA framework. Briard et al. (2020) and Bikas et al. (2019) are other examples of holistic DfAM frameworks that consider multiple disciplines in the DfAM process. Renjith et al. (2020) show an example of how a database with CAD features can be used to create different design solutions, and Müller et al. (2021) utilizes a EFM to achieve similar result. Borgue et al. (2021) combine geometrical parameters with manufacturing settings and compare weight, manufacturing time and cost during design. Li et al. (2019) use what they call a multiview model, which stores component information to achieve product simulation and optimization. Dordlofva highlights which design activities that need to be performed to qualify AM components (Dordlofva, 2020b). However, none of these authors conduct a formal holistic mathematical optimization including both product and process parameters as optimization variables.

DESIGN AUTOMATION FOR ADDITIVE MANUFACTURING

This chapter describes the DA framework for AM developed within the thesis and as part of that process aims to bridge the separate studies in the appended papers. The goal is to realize the framework presented in Figure 17 in order to create an environment for integrated AM product and process design. While the independent papers present different versions, aspects or details of the work, this section explicates how they are connected. Several of the appended papers describe the development of scripts, functions, and user interfaces, in addition, multiple commercial software programs for design and CAE evaluation are used. While the work in this chapter is presented as one cohesive framework, the developed computer tools are presently not integrated into one homogenous computer system. However, the developed tools constitute the different parts of the proposed framework.

Figure 18 presents an overview of the framework described in this section. The framework consists of four functional modules for defining, creating, evaluating, and optimizing a component (illustrated by blue squares). The modules contain best practices, successively developed throughout the work, based on a master model (MM) that connects the separate modules by carrying generic knowledge of the component. The functional modules can either be used as independent support or as a whole for defining, creating, evaluating, and optimizing a component.

Different versions and parts of the framework have been demonstrated and evaluated on various application cases. The following sections describe the MM and the four functional modules, while the application cases are presented in Chapter 6. Figure 18 shows also how the appended papers contribute to the framework. Paper I provides a first sketch of the architecture of the framework. Papers II-V contributes to developing methods and computer support for the four modules and evaluation of application cases. Finally, Paper V gives a more detailed description of the MM.

Figure 18. Overview of the developed DA framework. The four blue boxes are the functional modules where different automation steps are performed. The MM bridges the modules by carrying knowledge between the functions. How the appended papers contribute to the framework is described by the roman letters.

5.1. Master Model

The MM acts as a back-bone during the proposed DA process and carries information between the functional modules. The MM contains component functionality, geometry, manufacturing setup, analysis setup, design variables, objectives, and constraints. The MM as a concept is first introduced in Paper II but then further developed within Papers III and V.

The component is represented by a structure based on functional modeling and solutions of the functions. A solution element is characterized by inputs that describe the specific object. Each solution has different inputs, but they can be grouped into three types: references, relations, and information. References connect the solutions to each other or external references. Relations control the shape or size of the object, while information adds information not directly related to the geometry. An example of information is the required tolerances for the feature. Figure 19 shows an example of the functions, solutions of the function, and solution attributes.

Figure 19: Functional decomposition, solutions, and related attributes.

The MM is stored as an XML file, where the functional hierarchy is stored together with other information. An example of a simplified MM scheme is visualized in Figure 20. CAE analyses are stored in the model by a list that keeps track of coupling to external analyses functions, required inputs, and responses. Similarly, lists with variables and their limits, formulas, and optimization objectives and constraints are stored in the file. Finally, the

AM setup in terms of material, machine, positioning and build direction, and post-processing steps are represented.

Figure 20: Example of a simplified scheme representing the MM, from Paper V.

5.2. Design Configurator

The design configurator creates a component, based on selecting solutions that solve functions and references. A simple graphical user interface (GUI), developed within Paper V, aids this process. The GUI enables the user to connect to CAD software, create solutions, and add couplings to CAE functions. Figure 21 shows the information flow where this information is saved into the XML MM when saved.

Figure 21: Schematic of the information flow from the GUI to the MM.

The configurator is split into tabs, categorized into three types; general setup, creation of the geometrical solution, and setup of analyses and optimization. In the general setup,

connection to CAD software and the AM and post-processing methods selection is established. The creation of geometrical solutions is split into one tab for each function solved by the solutions. An analysis is set up by selecting CAE type, what should be analyzed, and connection to external CAE tools. This tab contains functions for setting the limits of the design variables, and optimization goals and constraints (based on responses from the CAE setup).

An example screenshot from the GUI is shown in Figure 22. The fluid solutions tab is shown, and add channel is selected. In the pop-up window, input arguments are selected. The first input consists of a set of reference points, which are used to create the first placement of a channel. The second inputs are relations and information of the channel. This includes cross-section shape, area, and wall thickness.

Figure 22: The graphical interface developed to support the creation of new products used in the fluid power pump application.

5.3. Geometry Creation

While the MM contains overall product knowledge, including functions and solutions, it does not collect 3D data. For 3D data, a commercial CAD software is used that works in parallel to the MM. The creation of the geometry in the CAD software is performed by instantiation of CAD templates. Solutions data is read from the MM into the inference engine built by object-oriented programming. Each solution is represented by a class in the inference engine, which can create, change, and delete geometrical elements in the

CAD software. The geometry creation is utilized through externally stored CAD templates (see Papers II and V). The schematic of the process is seen in Figure 23.

Figure 23: Coupling between databases, MM, inferences engine, and CAD system.

The CAD templates are constructed by geometrical elements, parameters, and rules. The CAD model is created by topological instantiation based on the references, relations, and information saved in the MM. References in the instantiation can either be external or from earlier created elements. Parameters within the CAD templates are used for the control of morphological changes. Paper II describes how the hierarchy between CAD templates can be constructed.

The geometry is adapted to be manufactured by reactions in the CAD templates, which modify the geometry to fulfill AM rules. An example is a fluid channel where the internal cross-section is modified from a circular to a drop shape to avoid support structure (see Paper V). As shown in Figure 24, the top radius (r) and angle (α) are adapted to prevent support structure for the chosen AM process. The orientation of the drop is adapted to the build direction and is updated if the orientation changes.

Figure 24: Example of instantiation where the cross-section of a channel is automatically oriented to avoid support structure.

5.4. Design Evaluation

In addition to automatic AM compensation in terms of geometry modification, manufacturing evaluation is performed by an external CAE evaluation. The manufacturing

evaluation contains a check of AM design rules as well as cost calculations. The design rule evaluation is supported by a database that includes rules for different AM machines and post-processing methods. External CAE models perform the functional evaluation. In this process, a database with material properties is used to support the evaluation. All the separate CAE models are fed with geometries adapted for the specific discipline. Examples of such CAE evaluations are FE calculations, fluid flow calculations, manufacturing, and post-processing. An overview of this process is shown in Figure 25.

Figure 25: Connection between the evaluation functions and the other parts of the system.

5.4.1. Manufacturing Evaluation

The manufacturing evaluation is performed on an AM build model consisting of an STL representation of the geometry exported from the CAD system. AM and post-processing knowledge stored in the MM is used to compensate the geometry for manufacturing before the export. Figure 26 illustrates an example of where a geometrical feature used for attachment by rivet is compensated by the addition of stock material that is offset for manufacturing and post-processing (from Paper III).

Figure 26: Example of how an AM build model compensated for manufacturing and post-processing, from Paper III.

The manufacturing evaluation consists of a design rules check on the AM build model (i.e. the dashed line in Figure 26). From the design rules database, commonly accepted geometrical design rules for AM and post-processing are extracted. Parameters for specific machines are coupled to the design rules in the database. The evaluation is performed by

calculating a manufacturability feasibility (MF) index, where an $MF \leq 0$ means that the rule is fully satisfied.

Table 2 illustrates the implemented design rules, which are further expanded on and discussed in Paper III. This constitutes a first step toward manufacturing evaluation. However, it is possible to extend the framework with more complex simulations and assessments of the manufacturability of a specific component.

Table 2: Visual representation of the design rules database, from Paper III.

				AM machines	
	Rule	Description	Output description	EOS M400	Arcam Q20 plus
1	Fit within machine	The part(s) need to fit within the build area of the machine.	x,y,z (mm): Size of build chamber. If $x,y,z > 0$ a rectangular area is assumed (width, depth, height). If $x,y > 0$ & $z = 0$, a cylindrical chamber is assumed where x is radius and y height of chamber.	400, 400, 400	350, 380, 0
2	Smallest hole thickness	The smallest inner distance between two surfaces.	x (mm): Smallest hole size allowed.	0.2	0.4
3	Smallest wall thickness	The smallest outer distance of a wall or similar.	x (mm): Smallest wall thickness allowed	0.2	0.4
4	Support structure for overhangs	Support structure necessary to support overhang features.	x (deg), y (deg): x = overhang angle allowed for rough surfaces y = overhang angle allowed for fine surfaces	30, 45	30, 45

The manufacturing cost is calculated by a function that uses the AM machine, material, component volume, height and width of the component, and amount of support structure necessary as input. Any potential cost for manufacturing is added through a one-time cost based on a quotation from the sub-contractor, as explained in Paper III.

5.4.2. Functional Evaluation

Evaluation of the functional performance of a component is based on the functions which the incorporated solutions solve. CAE verification can either be performed using connected external tools (as presented in Paper III) or by internal procedures in the inference engine (as shown in Paper V). The connections are established through data saved in the MM. In this process, the inference engine receives input from different sources, calls the CAE simulation models (such as FE-models), and receives responses and presents them in the GUI

(shown in Paper V). The functional evaluations are based on the final component geometry, represented by the solid line in Figure 26.

Paper III presents a database containing material properties for different materials, AM machines, and post-processing combinations, which are used to support the evaluation. Table 3 shows the principle of how the material database is structured.

Table 3: Material properties database, originally from Paper III.

Material	Machine:				
	Properties	EOS M400 Ti64	EOS M400 + centrifugal finishing Ti64	Arcam Q20 plus Ti64	Arcam Q20 plus + centrifugal finishing Ti64
Ti6Al4V	Static				
	- Young's modulus (GPa)	110	110	120	120
	- Poisson's ratio (-)	0.3	0.3	0.3	0.3
	- Density (kg/m³)	4410	4410	4430	4430
	- Yield Strength (MPa)	800	800	1020	1020
	- Ultimate Strength (MPa)	860	860	951	951
Ti6Al4V	Fatigue Stress at failure (MPa) as function of number of cycles (x)	$2797.5 \cdot x^{-0.161}$	$1286.7 \cdot x^{-0.051}$	$1683.6 \cdot x^{-0.156}$	$1463.1 \cdot x^{-0.107}$

5.5. Design Optimization

The final part of the proposed DA framework is an optimization module that is used to explore and evaluate design solutions. The list of variables, variable limits, and functional goals in the MM are used to structure the optimization. As shown in Figure 27, an optimization engine is used to modify the parameters and call the design evaluation module, which responds with functional performance and manufacturability measures. The optimization module then drives this loop until an optimal parameter setting is identified and one or several Pareto optimal designs are obtained.

Figure 27: Information flow to and from the optimization engine.

The optimization is performed by a distributed MDO framework consisting of two levels. First, on a global MDA level, the manufacturing setup of the AM machine, post-processing

options, and material are modified. In a subordinate optimization, geometry and manufacturing variables (component placement in the machine and build direction) are altered. Figure 28 describes the MDO framework according to an XDSM (Lambe and Martins, 2012). The ovals represent drivers in the framework, the rectangles are computer analyses or processes, and parallelograms are variables or information. Information (or variable) flow is described with broad lines, and process flow is described with thin black lines. The optimization framework and setup are further presented in Paper III.

Figure 28: An XDSM describing the MDO procedure.

APPLICATION CASES

Various parts and versions of the DA framework proposed and presented in Chapter 5 have been applied to three different industrial applications: an upright for a formula student race car (Paper VI), an aircraft cargo door bracket (Papers II and III), and a hydraulic pump (Papers IV and V). This chapter briefly introduces the design process for two of the applications (aircraft cargo door bracket and hydraulic pump) where the framework has been implemented in its most prolonged state. For a more detailed description of the implementations, see the separate papers.

6.1. Airplane Bracket Re-Design Study

A component placed on an airplane cargo door, today produced using traditional manufacturing, is re-designed based on AM technologies in the airplane bracket case. As shown in Figure 29, the part is placed between an actuator used for opening and closing the door and the cargo door itself. The actuator will push (and pull when closing) at the component at different angles depending on the position during opening and closing maneuvers. The movement and the changing gravitational forces, together with aerodynamic loads (e.g. the wind conditions), create structural forces that the door needs to withstand. The component is fastened to the actuator by a bolt with a given interface. Connection to the cargo door is performed by rivets placed at different areas at the door where some rivet placements are fixed, whereas others can be set freely, see Figure 30.

Figure 29: Overview of the aircraft cargo door and the studied component.

Figure 30: Detailed interface between actuator, case study component, and cargo door.

The goal of substituting the traditional manufacturing process for AM is to create a design with a lower mass while considering the structural forces. A second objective is to minimize the manufacturing cost.

The proposed automation framework was complemented with TO during this design process. Based on the concept received from the TO, the DA framework was used to create a CAD geometry, evaluate the design, and for further optimization of the component, as the topology optimized part is not fit for production. The process steps are shown in Figure 31.

Figure 31: Design process for the airplane bracket.

6.1.1. Result from the Aircraft Bracket Re-Design Study

A geometry was created by using the given interface placements and points extracted from the TO output. Solutions for the attachment type rivets and bolts together with solutions for structure elements were used to build up the design. Figure 32 shows both the TO result (in dark green) and the interpreted design aided by the DA framework presented in Chapter 5 (lighter color). A more detailed description of the process is given in Papers II and III.

Based on the geometry presented in Figure 32, an optimization problem was formulated, as shown in Equation 2. The problem is formulated as a multi-objective optimization problem of simultaneously minimizing the component weight and manufacturing cost while considering static and fatigue structural load cases. The design variables $\mathbf{x}$ (108 geometrical design variables automatically based on the selection of functional solutions) and $\mathbf{y}$ (AM settings) were used to explore design solutions.

Figure 32: TO result of the component (green), together with a version of the parametric CAD model created by the DA framework.

$$\begin{aligned}
\min \quad & F(\mathbf{x}, \mathbf{y}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}, \mathbf{y})\} && (f_1 = \text{mass}, f_2 = \text{cost}) \\
\text{s.t.} \quad & g_1(\mathbf{x}) < S_{\max, \text{static}} && (\text{static structural constraint}) \\
& g_2(\mathbf{x}) < S_{\max, \text{fatigue}} && (\text{fatigue structural constraint}) \\
& g_3(\mathbf{x}, \mathbf{y}) \leq 0 && (\text{design rule 1}) \\
& g_4(\mathbf{x}, \mathbf{y}) \leq 0 && (\text{design rule 2}) \\
& g_5(\mathbf{x}, \mathbf{y}) \leq 0 && (\text{design rule 3}) \\
& X_{i, \min} \leq X_i \leq X_{i, \max} && (\text{geometry parameters, } i = 1, 2, \dots, 108) \\
& Y_{j, \min} \leq Y_j \leq Y_{j, \max} && (\text{manufacturing settings, } j = 1, 2, \dots, 5)
\end{aligned} \tag{2}$$

The MDO framework presented in section 5.5. was used to compare four alternative AM and post-processing combinations. An Arcam or an EOS machine could perform the AM process, and centrifugal finishing usage was optional. The framework evaluated manufacturability, cost, and structural performance as described in Chapter 5.

A comparison between some of the obtained Pareto optimal design solutions for each machine is shown in Figure 33. An illustration of designs 1 and 4 in the AM build chamber of the respective machines is shown in Figure 34. Note that even though the designs appear similar, there are differences in the geometries, and the optimization has rotated the build direction by 90 degrees in the EOS machine. Design 1 was manufactured and is shown in Figure 35. The goal was to achieve a weight reduction compared to a baseline design of 1.8 kg, which was achieved with a 30 percent margin.

Figure 33: Comparison between some of the design solutions' objective values.

Figure 34: Comparison between the AM setup of designs 1 (left) and 4 (right) from the Pareto front in Figure 35. The yellow surface represents the build chamber, and the green lines represent the support structure. Please note that it is a simple visual representation and not the actual support structure.

Figure 35: One design manufactured by an Arcam machine, centrifugal finished, and with interface surfaces machined to achieve the desired tolerances.

6.2. Hydraulic Pump Re-Design Study

The study of the hydraulic pump examines a hydraulic axial piston pump of the swash-plate type (Murrenhoff, 2014). This pump works by rotating a wobble plate, making ten pistons stroke, building up the system's pressure. As seen in Figure 37, the pump has one inlet and two separated outlets where each second piston leads to the different outlet alternatives. The goal of the design process is to improve the internal flow characteristics by re-designing the channels. As the channels are manufactured using traditional drilling,

they will lead to sharp bends and, hence, lots of fluid losses. Secondary goals are weight reduction and reducing the number of parts in the pump, i.e., part consolidation.

The DA framework from Chapter 5 was utilized in this process after initial system analysis and design steps. As shown in Figure 36, the geometry creation and design evaluation steps from the DA framework were applied in the process.

Figure 36: Design process applied during the design of the hydraulic pump.

6.2.1. Result from the Hydraulic Pump Re-Design Study

During the re-design process, two hydraulic flow modifications were in focus. First, a general desire to improve the flow characteristics by improving the channels bend radiiuses. Secondly, the pump is re-designed to have two outlets with similar flow characteristics by creating two parallel outlets instead of one outside the other. Compared to the original design, three parts were consolidated into one, reducing the number of parts in the assembly by two. Also, thanks to AM, it was possible to reduce the weight of the component by 35 percent (i.e. 3kg) by adding an internal cavity in the piston block, see Figure 38.

To quantify the results, a model developed within Paper IV calculates pressure losses in the pump. Table 4 presents a comparison between the pressure loss between the piston and the two outlets in the original and re-designed pump. Based on three gradually increasing rotational speeds, it is shown that the re-designed pump decreases the pressure loss by 45 to80 percent and creates a more consistent flow between the two separated outlets.

Figure 37: Cross-section of the original pump.

Table 4: Comparison between the pressure loss in the original design and the re-design.

Study	Outlet	Pressure loss (MPa)		
		500 rpm	750 rpm	1000 rpm
Original design	1	0.55	0.68	0.85
Original design	2	0.91	1.72	2.60
Re-design	1	0.30	0.34	0.40
Re-design	2	0.29	0.33	0.37

Figure 38: Test print of a cross-section of the pump.

DISCUSSION

This chapter discusses the strengths and weaknesses of the work performed within the thesis. This is accomplished by first discussing the methodological approach used, followed by highlighting the contributions of the work. Finally, a discussion of some of the limitations of the thesis follows, including both the research process and the result of the work.

7.1. Method Discussion

The research projects within this work have been performed in close collaboration with industrial partners. Based on this, it was natural to apply the industry-as-laboratory approach where industrial challenges are used as a source of inspiration and for performing experiments. The DRM methodology was chosen since it is developed for this kind of research, and it is easily accessible and straightforward. Also, the collaboration partners offered good possibilities for conducting the descriptive studies.

Since the DA framework and application cases are developed in parallel, there is a risk that the methods are biased and too adapted for the specific cases. With the relatively few cases used, it is a risk that the developed framework is difficult to adapt in new products and areas. To counteract this, the two application cases of the separate projects are of significantly different nature, contributing to the generality of the developed DA for AM method. Outside the scope of this work, the methods have also been presented for and discussed with other researchers and companies. It has also been applied by master students in educational settings in several different projects. Hence it is believed that the methods are applicable in a broader perspective. However, this will require an extension of methods and models, and include further validation studies, an appropriate area for further research.

The most straightforward explanation of the applied method is that a hypothesis, in the form of a new DfAM approach, is proposed within Paper I, and then Papers II to V are used to test the hypothesis. This description of the process is similar to a classical hypothesis testing form of research. However, it is effortless to rebut this description by stating that no actual falsification of the hypothesis is performed. Instead, Papers II to V are used to prove that the hypothesis is true. One can even argue that the work is performed by ad hoc hypothesis testing, where the methods are constantly updated and refined based on

progress. The counter-argument is that the base hypothesis is not changed but rather refined, which is allowed according to Popper (Andersen and Hepburn, 2016). The methods and support developed throughout the work do not aim to change the initial hypothesis but rather create methods that aid the testing.

As described in Chapter 2, the work is conducted within two research projects, AddMan and AMHY. The first (AddMan) was performed in close collaboration with representatives from the aeronautic industry, experts on AM, and researchers focusing on material characterization. The environment fitted well for a broad approach where this work collected information from the different experts and literature and applied them in the product development process. The structured literature review presented in Paper I was performed early in the AddMan project and my Ph.D. process. Therefore, it worked both as a way to learn more about AM and DfAM and a way to fit the other project partners' work in a product development context. In addition to the structured method for finding and selecting relevant research, the work required a considerable pre-study where literature was used to identify which topics were interesting. Papers II and III present the first version of the proposed DA framework together with an application case from the AddMan project.

In the second project, AMHY, the work was conducted in close collaboration with an academic expert in hydraulic power, with an application from an industrial partner. Paper IV was performed in this constellation where the domain expert co-authored to ensure application correctness and relevance. Compared with the aeronautic application, where the application of AM came as a pull from the industry, the hydraulic pump application used within Papers IV and V is more of a technology push. Therefore the review in Paper IV is explorative where the aim was to find applications similar to a hydraulic pump. Using a hydraulic pump in a second application case seeks to explore the opportunities of using AM for manufacturing pumps and test the proposed DA framework in a new environment. In Paper V, the proposed DA framework is adapted to the new application by incorporating solutions adapted to a hydraulic pump. The paper also emphasizes some of the limitations in the developed DA framework and proposes solutions.

Papers I, II, III, and V are written with the same author constellation. As described above, this does not imply that the work has been developed without input or feedback from others. The work has continuously been shared with experts both from academia and industry. With reference to Buur (section 2.1.2.) and the discussion above, the research is considered to be verified by acceptance by both industrial and academic peers. Logical verification of the work is performed by ascertaining that the work, to a large extent, is built on and adapting current methods. The framework can also clearly explain the outcome of the application cases. Furthermore, the research is considered to fulfill the degree of novelty, as demanded by Olesen (1992), as new methods and tools for DfAM are presented. In the following section, these contributions are positioned to state of the art in industry and academia.

7.2. Contributions

In this section, the contribution of the work is discussed from academic and industrial perspectives. Academic contributions aim to advance the knowledge of the research community, while industrial contributions focus on advancing a company or industry branch.

7.2.1. Academic Contributions

The academic contribution consists of two literature studies and the proposed generic DfAM DA framework. The first literature study (Paper I) focuses on state of the art within DfAM and presents current methods and their connection to the design process. This work contributes to the research field with a compilation of relevant literature and how they relate to each other and the product development process. This review fills a gap in the literature, as most papers within the field of AM are not directly linked to the product development process. Furthermore, the tools and methods that support AM usage in the development process are an under-researched area. The fact that Paper I is highly cited supports the claim that it fills a gap in the literature.

The second literature study (Paper IV) aimed to identify current knowledge associated with additive manufacturing of fluid applications and especially in fluid power and hydraulic pumps. Academic contribution is achieved by highlighting the gap in research, which is the design and manufacturing of hydraulic pumps. The work relates current research in nearby areas such as coolers, heat exchangers, and hydraulic manifolds and states that similar design and optimization methods should be possible to apply in pump design. The work expresses potential benefits that can be gained by introducing AM and points out further research needed.

The DA framework proposed within this work is based on the first of the two reviews. Based on the review, the potential of automation in the DfAM process is identified, but gaps that need to be filled are also emphasized. The aim of the proposed DA framework is to overcome the design paradox (see Figure 1) by creating an environment for integrated product and process development. The main contribution of the framework is the possibility to simultaneously change geometrical, manufacturing, and post-processing parameters and get feedback on how these affect functional performance, manufacturing feasibility, and cost. It is also showcased how MDO can be utilized for optimization in the framework.

Compared to other holistic DfAM methods, this work is similar to the work presented by Renjith et al. (2020) when it comes how to handling CAD geometries. The possibility to compare how geometrical and AM setup affect functional and manufacturing characteristics can be compared to the work by Borgue et al. (2021). Neither of these applies MDO to explore different alternatives and find optimal solutions. Li et al. (2019) both use a multiview model similar to the MM in this work and apply optimization for various disciplines.

However, the work does not have the same holistic view in creating new designs and is dependent on an initial design.

Geometrical creation in the frameworks combines methods for functional modeling (Ullman, 2010) and HlCt (Amadori et al., 2012). While there exist approaches that create intrigue coupling between functions, constraints, and solutions, such as (Müller, 2020a), this work only utilizes functional modeling to identify possible solutions, and hence does not have the same modeling depth as Müller. Instead, the focus lies in combining solutions of functions with object-oriented programming and HlCt to create CAD models. The HlCt approach enables geometry creation by CAD templates that utilize AM knowledge to adapt the created geometry to an AM process automatically. This can be compared with the method applied by Biedermann et al. (2021; 2020) but with a connection to the MM, which keeps track of the features and variables and therefore enables MDO in an efficient manner.

A material database with material properties for different manufacturing setups is included in the framework. This enables automatic functional validation of components with the correct properties for the setup. The work also contributes to the formalization of AM design rules into a database that is applied in the MDO framework. Research that automatically evaluates design rules exists (Rudolph and Emmelmann, 2017), but the methods are not adapted to be used in an MDO environment. The work in this thesis is also unique in separating the model used for manufacturing evaluation from the one used for functional assessment.

The creation of separate models used in different parts of the framework leads to the contribution of the MM. The MM approach describes how knowledge can be saved within the DfAM process to automate the creation, evaluation, and optimization of AM design. Compared to similar MM and extended product model approaches proposed (Heikkinen, 2021; Sandberg et al., 2017; Tyapin et al., 2012), this work more explicitly adapts the concept of a MM to an AM context and incorporate AM machine selection and setup.

Overall, the presented framework enables some possibilities not available in other methods and frameworks. It also defines what is needed to achieve MDO in a DfAM setting, which benefits this can have, and how different methods and models need to be adapted to fit the process. While other work (some of which are discussed above) do individual steps of this process more thoroughly than the work in this thesis, the holistic perspective applied in adapting the methods to make them fit together in an MDO framework is one of the main contributions of the thesis.

7.2.2. Industrial Contributions

From an industrial perspective, the work contributes by applying the DA framework on two components directly from the industry to showcase the applicability of the proposed framework. Hence it is shown how the framework is useful in real industrial settings.

The first application is from the aeronautic sector, a conservative industry that requires comprehensive investigation and verification before adapting to new technologies. However, AM is relatively well established within the aeronautical industry compared to other businesses, even though seldom used in flight-critical components. The application case contributes with a confirmation that AM can be used in aeronautics and what profits and challenges come with it. For the specific test case, the weight could be reduced while maintaining the same functional performance. Hence it is shown that the functional performance of aeronautical components could be increased by the usage of AM.

The fluid power industry in general, and hydraulic pump manufacturers in particular, are on a much lower technology readiness level than the aeronautical industry when it comes to the adaption of AM. The review of AM of hydraulic components and the application case contributes to general knowledge advancements at the case company and the sector. This is vital as AM has the potential to revolutionize the fluid power industry. In the application case, it is shown how AM can increase the performance (in terms of reducing the fluid losses), reduce the component weight (by minimizing the amount of material needed), and at the same time reduce the number of components in the pump (and hence reduce the cost of assembly). The thesis shows that AM brings many advantages to the fluid power industry, and the proposed DA framework demonstrates how this can be achieved in practice.

Furthermore, the work has the potential to decrease the development time of products by supporting the design process and reducing the manual work from function identification to manufacturing data. The framework, which incorporates cost, manufacturing, and function models, enables the user to get direct feedback on how changes in design or AM setup will affect performance and cost. Together with the possibility of adding additional and more detailed simulation models, the proposed design process can create a design process where the engineer increases their product knowledge earlier in the design processes. Direct export of manufacturing and post-processing information aids the processes of changing late in the process. The direct cost and manufacturing feedback can also help introduce AM into new industries where the knowledge of the AM process is modest.

7.3. Limitations

As a critical person and author, I am the first to admit that the work has limitations and shortcomings. At first, it is essential to emphasize that the DA framework proposed within this work is one way to achieve a more automated design process for AM, whereas there exists, of course, many alternative ways. The proposed framework is in its simplest form proposed already in Paper I and then later developed throughout the thesis. Based on the first literature study, it was identified that applying MDO on a higher level in the DfAM process was an attractive way forward. However, as Maslow (1966) states, there is always

a risk that everything looks like a nail if the tool you have is a hammer. This work proves that an MDO approach can be applied to the DfAM process, but nothing in this work states that this should be the only or the best way to overcome the challenges in the DfAM process. Nevertheless, MDO and DA have proved to be efficient ways of improving the development process in many other domains, such as aeronautic engineering (Papageorgiou, 2018), industrial robots (Tarkian et al., 2012), and engine development (McAllister and Simpson, 2003).

It is also necessary to say that the scope of the work is extensive and includes everything from a design idea to a post-processed component. While this is a powerful strength and main contribution to the thesis, it also makes it impossible to go into detail in every design step. Where many other research projects participate in part of the design process and solve them very well (as described in Chapter 3 and 4, and discussed in section 7.2.), this work paints with a broader brush. It accentuates the need for a holistic view during the development of DA support. With this said, almost every part of the framework can be more developed and evaluated further. For practically every model and analysis that is used in the thesis, there is the option to conduct a more thorough analysis with more detailed models. However, it is assumed that the level of detail used in the thesis is deep enough to showcase the usefulness of the proposed framework in general and the applicability of AM in the test cases. Still, it is essential for future research to develop more detailed models for the design and analysis of components performance as well as the AM manufacturing process and post-processing. In this work, functional modeling of the components is only used to decompose a component and identify potential solutions. More thorough modeling methods exist and have shown a potential of being used to identify more intricate couplings between function, constraints, and geometry (Müller, 2020; Borgue et al., 2021). Future studies should focus on utilizing these kind of methods during the creation of new solutions in the framework. Also, this work has studied a limited number of applications, considering two different AM-machines, and only the most severe design constraints etc. Hence the implementation in terms of functions and solutions modeling, material data, design rules etc. is not complete by any means, and need to be further developed.

A limitation of the work is also that it does not carefully investigate which demands particular industries would have on the component. Specific guidelines from the aeronautic sector are incorporated in the HlCt when it comes to e.g. minimum radius of material around a rivet. Still, no general investigation on the demands or how they can be considered generally is considered. Future work should focus on how qualification aspects, as the once shown by Dordlofva (2020), can be incorporated in an MDO for AM framework.

The technical implementations, such as the GUI, number of options for creation of solutions, flexibility, and quality in CAD models, are other areas in need of improvement. Since the work is not in software development, this itself may not be a significant problem. However, the lack of usability counteracts the possibility of evaluating the framework's

usefulness in real industrial settings. In the design cases, the proposed framework is applied by the author. However, for a more thorough evaluation in a real industrial setting, the framework should be used by more researchers and industrial practitioners and in other applications. This could be realized once the system is more mature in terms of, for example, detection and elimination of bugs. Several hours of work (preferably by a more experienced software developer) needs to be performed to solve this problem.

CONCLUSIONS AND FUTURE WORK

This chapter completes the thesis with a presentation of the conclusions drawn from the work. This is performed by relating the thesis findings to the four goals stated in the Introduction in Chapter 1. Based on the findings, a final section will create new perspectives by presenting possible directions for future work.

8.1. Conclusions

8.1.1. Research Goal 1

Identify state of the art in the DfAM process, including trends related to DA and design optimization in the DfAM process, and potential gaps.

Paper I presents an extensive literature review of methods and tools in the DfAM process. Paper IV complements Paper I with a focus on hydraulic applications manufactured by AM. Together the two papers give extensive insights into the state of the art of AM in general and support tools for DfAM in particular. Paper I also present research dealing with DA in the DfAM process and, based on current knowledge, proposes an MDO process that bridges different disciplines in the field.

While many subfields in DfAM are extensively explored, this work maps existing methods into a product development process. The proposed DA framework covers the entire product development process and includes steps from concept generation by function decomposition to post-processing. Compared to current DA and optimization methods, the method proposed in this work combines part design with AM machine selection, AM setup, and post-process selection. This makes it possible to compare parts optimized for different manufacturing setups without any manual work.

8.1.2. Research Goal 2

Develop DA methods that support the DfAM process.

Papers II, III, and V present methods which develop the overall DA framework for AM sketched in Paper I. The methods in Papers II and V focus on the creation of geometries in parametric CAD software and how the geometry can be adapted to AM and post-processing. Generic product development methods for functional decomposition are used to break down products and find solutions. The solutions are coupled to geometrical templates and thereby related to a CAD model. Paper V also displays how AM design rules can be built directly into the CAD templates to ensure manufacturability. In addition, Paper V illustrates how this information, together with other knowledge used in the DA process, can be saved in a master model and used in downstream design steps.

Paper III focuses on methods for manufacturing evaluation and optimization in the DfAM process. Commonly accepted AM design rules are formulated to be saved in a database and used for automatic manufacturing evaluation. Similarly, a method for storing material data for AM and post-processing combinations to be used in CAE evaluation is shown. A cost model is also adopted to estimate the cost of manufacturing based on geometrical and manufacturing evaluation data. Finally, the paper demonstrates a multi-level MDO framework for optimizing AM components based on manufacturing and CAE models.

8.1.3. Research Goal 3

Demonstrate computer systems that utilize DA to support the DfAM process.

In Papers II, III, and V, the methods presented are implemented into computer systems supporting the DfAM process. The computer systems showcase the applicability of the methods and evaluate their performance. The implementations work as proofs-of-concept and demonstrate that it is possible to create working tools of the proposed methods. Focus in the development is the back-end programming functions that automate repetitive parts of the work. As a result, several scripts and computer functions for geometry creation, evaluation, and optimization can either be used independently or together as one framework. In addition to the back-end development, Paper V shows a first sketch of a GUI for user interaction.

8.1.4. Research Goal 4

Evaluate the developed methods and computer systems based on gains in the DfAM process.

Different application cases are used to evaluate the methods and tools developed. Papers II and III show a component from the aeronautics industry where the goal is to minimize weight while respecting structural integrity. The second application comes from Papers IV and V and is a hydraulic pump where the main goal is to reduce pressure loss. In both

cases, the developed framework succeeds with the design goal and creates products with better functional performance than existing designs. Hence, it is shown that the tools work and are able to produce reliable results. However, no studies have been performed where the traditional way of working is compared to the process of working with the proposed framework. This is an apparent area for further work.

The optimization applied to the aeronautic component is computationally expensive, but the manual work is judged to be equal to the creation of geometry with state-of-the-art software. In addition to a better product, the gains of this method are the potential of comparing different manufacturing setups and the ability to create geometries for different CAE analyses and manufacturing evaluations automatically. The hydraulic pump application shows how AM rules are automatically considered, and the geometry is also adopted if the build direction is changed.

In summary, it is judged that the proposed framework creates a more flexible environment for the creation of AM components where alternatives both in geometry and manufacturing can be investigated. This is a step toward overcoming the product development paradox (see Figure 1), where the design freedom and knowledge regarding design and manufacturing increase early in the project.

8.2. Future Work

To further evaluate the proposed framework, a natural next step would be to test the framework on more design studies. These studies should be in different settings with professional design engineers from multiple disciplines to get maximum feedback. That is to evaluate and improve the proposed framework using testing in realistic industrial settings.

In an academic context, several further studies which can be used to improve the proposed framework would be interesting. An exciting potential is to incorporate methods or software that simulate the AM process to achieve higher fidelity in the manufacturing evaluation. While this would increase the likelihood of successful manufacturing, a problem could be the increased simulation time. Furthermore, the CAE models used for functional evaluations can be improved as well. Then, a general study of model fidelity and optimization setup in relation to the trade-off between successful results and development time can improve the framework's usability. Extended implementation of functional decomposition and modeling to aid in identifying design constraints and support the functional modeling is another area with great potential.

Other work that can be conducted in academia is investigating how different geometrical creation and manipulation methods can be combined to create better, more detailed CAD models. Together with the development of TO tools, several design cases can probably be gained by a tighter integration between TO results and the framework in this thesis. By using methods for feature recognition, a potential is to automate the creation of CAD

features based on TO results. Another interesting area related to creating geometries is to include CAD templates inspired by design heuristics.

The computer implementations' usability and overall quality should be improved for the methods presented in this thesis to be further used in the industry in a broad sense. Also, the databases used to showcase the proposed framework, i.e., the design rules, material data, number of AM machines etc. need to be extensively enlarged and improved to increase the framework's usefulness.

Finally, even though there are numerous areas for future work, the thesis form a strong foundation for continued development of DA within DfAM and the wider introduction of AM in the industry in general.

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Papers

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