Thesis for The Degree of Licentiate of Engineering

The Role of Digitalisation in Early Design for Additive Manufacturing

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Abstract

Additive Manufacturing (AM) offers various advantages in both product design and supply chain. However, its industrial uptake has been less than initially expected, with digitalisation as a significant but often overlooked obstacle. At the same time, design plays a crucial role across the product lifecycle. This thesis, therefore, explores the impact of digitalisation on Design for Additive Manufacturing (DfAM). Key findings reveal that the AM process requires tailored data management, information flows, and knowledge management strategies. To benefit fully from AM, it is essential to understand both its advantages and the conditions necessary to achieve them, revealing a practical knowledge gap.

This research identifies that current design and manufacturing process selection methods frequently overlook the need for early design-phase suitability analysis, critical for maximising the effectiveness of DfAM guidelines. The findings suggest that AM design may require a precise formulation or, in some cases, reformulation of requirements. Additionally, systematic strategies are required to collect and manage information and data supporting informed manufacturing decisions.

To address these needs, the Manufacturing Process Decision Support (MPDS) method was developed, incorporating key factors influencing manufacturing process decisions. This structured approach facilitates assessing the feasibility and suitability of AM in the early design phase, enabling greater benefits from DfAM guidelines.

Future directions include validation of MPDS in an industrial setting. Further, Artificial Intelligence (AI) and Machine Learning (ML) techniques can be explored to advance decision support by enhancing data collection, organization, and analysis. The integration of sustainability assessments in such early decision-making remains essential but underexplored, a critical step toward achieving widespread and "proper" industrial adoption of AM.

Keywords

Engineering Design, Digitalisation, Design Support, Additive Manufacturing, Design for AM, Decision Making

List of Publications

Appended Publications

[**Paper A**] Mallalieu A., **Hajali T.**, Isaksson O., and Panarotto M., *2022, "The Role of Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing"*
Proceedings of the Design Society, Volume 2: Design 2022, 1401-1410, doi:10.1017/pds.2022.142).
Author contribution: Hajali acted as a joint first author with Mallalieu and contributed equally in paper planning and writing. Isaksson and Panarotto contributed with knowledge and critique to the paper's idea, content and form.

[**Paper B**] **Hajali T.**, Mallalieu A., Brahma A., Panarotto M., Isaksson O., Stålberg L., and Malmqvist J., *2023, "Information Flow Analysis Enabling The Introduction of Additive Manufacturing for Production Tools-Insights from an Industrial Case"*
Proceedings of the Design Society, Volume 3: ICED2023, 2315-2324, doi:10.1017/pds.2023.232).
Author contribution: Hajali acted as the main author. Empirical studies were conducted in collaboration with Mallalieu. The remaining authors contributed by facilitating industrial collaborations and offering valuable insights to refine and improve the paper's quality.

[**Paper C**] **Hajali T.**, I. Hallstedt S., Isaksson O., *2024, "Sustainability Implications of Using Additive Manufacturing for Production Tool Design"*
Proceedings of NordDesign 2024, 382-391,
doi:10.35199/NORDDESIGN2024.41.
Author contribution: Hajali acted as the main author. I. Hallstedt and Isaksson provided valuable inputs to enhance the paper's quality, especially in terms of structure and content.

[**Paper D**] **Hajali T.**, Brahma A., Isaksson O., Malmqvist J., *2024, "A Decision Support Tool for Feasibility and Suitability Analysis of Additive Manufacturing in Pre-Conceptual Design Phase"*
Submitted for journal publication.
Author contribution: Hajali and Brahma collaborated in both planning

and writing the paper. Isaksson and Malmqvist provided ongoing guidance throughout the process.

Other Publications

The following publications helped addressing the research problem but not directly related to the research questions to be added to the main body of the book.

- Arjomandi Rad M., **Hajali T.**, Martinsson Bonde J., et al., *"Datasets in design research: needs and challenges and the role of AI and GPT in filling the gaps." Proceedings of the Design Society. 2024;4:1919-1928. doi:10.1017/pds.2024.194.*

- Despeisse M., **Hajali T.**, Hryha, E., *2023, "Sustainability in Additive Manufacturing" Encyclopedia of Sustainable Technologies (Second Edition): 533-547. doi:10.1016/B978-0-323-90386-8.00123-6.*

- Isaksson O., Brahma A., **Hajali T.**, Ohlsson D., and Mallalieu A., *2024, "The Importance of Digitalisation in Industrialising Additive Manufacturing: Learnings from the DIDAM P2030 Project" Advances in Transdisciplinary Engineering, 52, 442-452, doi: 10.3233/ATDE240187.*

- Lawand, L., **Hajali T.**, Al Handawi, K., Brahma, A., *2023, "Industrialization of Additive Manufacturing: Assessing the Impact of Excess Margins on Manufacturing Costs." ICORD 2023. Smart Innovation, Systems and Technologies, Vol 346. Springer, Singapore. doi: 10.1007/978-981-99-0428-0_22).*

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Contents

Acronyms

AHP Analytic Hierarchy Process
AI Artificial Intelligence
AM Additive Manufacturing
BJT Binder Jetting
CM Conventional Manufacturing
DED Directed Energy Deposition
DfA Design for Assembly
DfAM Design for Additive Manufacturing
DfM Design for Manufacturing
DfX Design for X
DRM Design Research Methodology
DSI Descriptive Study I
DSII Descriptive Study II
IoT Internet of Things
MCDM Multi-Criteria Decision Making
MEX Material Extrusion
ML Machine Learning
MJT Material Jetting
MPDS Manufacturing Process Decision Support
OEM Original Equipment Manufacturer
PBF Powder Bed Fusion
PLM Product Lifecycle Management
PS Prescriptive Study
RC Research Clarification
RQ Research Question
SHL Sheet Lamination
SME Small and Medium-sized Enterprises
TOPSIS Technique for Order of Preference by Similarity to Ideal Solution
VPP Vat Photopolymerisation

Chapter 1

Introduction

The introduction gives a background to the research in Section 1.1 followed by an overview of the research scope in Section 1.2 and an outline of the thesis structure in Section 1.3

1.1 Background

Historically, deciding on what manufacturing technology to use for a certain design was often relatively straightforward, since sufficient knowledge and experience of most commonly used manufacturing methods were well established. For example, transitioning from a manual to a highly mechanised process significantly improved textile production during the first industrial revolution. Here the decision to use machines instead was straightforward as it had the potential to produce cheaper, faster and more reliable products (Cartwright, 2023).

The Second Industrial Revolution further enhanced manufacturing with the rise of electrification and the widespread adoption of machinery. The application of electric power in factories led to continuous production, enabling factories to operate at higher efficiency and lower costs. This shift from manual labour to electrically powered machinery was a straightforward decision for manufacturers, as it directly resulted in enhanced operational efficiency and profitability (Mokyr, 1998).

However, the rise of automation and computerization in the third industrial revolution introduced new complexities to the decision-making process. Manufacturers began incorporating programmable machines, robotics, and digital solutions into their operations, which allowed for more flexible and precise manufacturing. Yet, these advancements also expanded the range of options available, making process selection more complicated (Naboni & Paoletti, 2015). Today, the rise of Industry 4.0 and 5.0 has made manufacturing decision-making increasingly complex. The manufacturing sector needs to consider not only productivity and efficiency but also human factors and broader sustainability

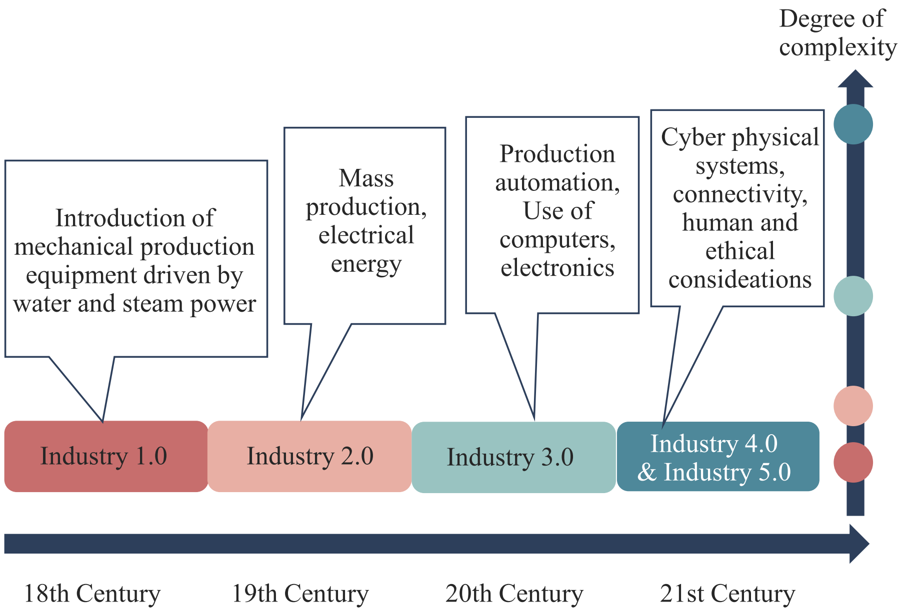

Figure 1.1: Overview of the industrial revolutions indicating the relative level of complexity, adopted from (Rutkowska & Sulich, 2020)

concerns. Technologies such as the Internet of Things (IoT), AI, and advanced robotics offer substantial opportunities for innovation but also require a more tailored and strategic approach to technology adoption (Akundi et al., 2022). While earlier industrial revolutions offered relatively clear choices based primarily on improving performance and reducing costs, today's complex environment necessitates a deeper evaluation of comparison between competing technologies and processes. In Figure 1.1 a summary of the industrial revolutions and relative complexity levels are demonstrated.

In this modern industrial environment, digitalisation is no longer an optional advantage but a vital enabler of industrial progress. Digitalisation including data management systems and simulation tools are becoming essential elements in integrating new technologies into manufacturing processes. One of the prominent innovations closely tied to digitalisation is Additive Manufacturing (AM) (Khorasani et al., 2022) as a digital model is transferred to the AM machine, and the manufacturing process relies on precise process control, where sensing process data is integral to the control loop necessary for achieving high-quality prints

In AM, parts are manufactured successively which introduces opportunities for producing customized products with less material waste, thereby offering industries the potential to create higher-performing and more efficient products (Gibson et al., 2021). Despite these advantages, AM currently accounts for only 0.13% of global manufacturing (Wohlers Associates, 2023; Worldmetrics, 2024). The adoption rate is much less than initially expected, suggesting that benefits of AM are not yet fully realized across industries (Omidvarkarjan et al., 2023). Although AM is growing rapidly, with an annual growth rate of 20% (McKinsey & Company, 2021; Fortune Business Insights, 2023), it remains primarily confined to niche markets such as aerospace and biomedicine. In these sectors, the value propositions of AM are clear, as it enables the manufacturing of customised and lighter products in comparison to methods traditionally used. However, in other sectors, comparing AM with Conventional Manufacturing (CM) methods such as casting and forging remains complex and resource-intensive, as these traditional methods have long-established industrial systems and accumulated expertise, unlike AM. This complexity arises from the need to consider not only improvements in product quality and process efficiency but also a range of factors including sustainability and its various dimensions.

A significant challenge in this regard is the lack of clear guidelines and frameworks that aid in comparing AM with other manufacturing processes, particularly in the early design phase when detailed part geometry is not yet available. In practice, many industries view manufacturing process selection as an activity that occurs after the design phase (Beaman, 2015; Pereira et al., 2019). Typically, companies screen existing designs to identify geometries that are suitable for AM. However, to fully exploit AM's potential, parts often need to be specifically designed for AM (Tian et al., 2022). This design consideration is frequently overlooked, limiting the potential of AM, or even may result in non-printable definitions.

Furthermore, while much of the existing literature focuses on "how" to design for AM, less attention is given to "when" AM can be considered as a more suitable manufacturing method (Eddy et al., 2016). Therefore,

> Currently, there is a lack of comprehensive manufacturing process selection guidelines specifically tailored to AM in the early design phase when part detailed geometry is not yet defined.

This hinders wider and "appropriate" industrial adoption of AM (Kadkhoda-Ahmadi et al., 2019; Wang et al., 2017). This gap highlights the need for decision support systems that assist manufacturers in evaluating the comparison of AM with CM, particularly in the early design phase.

1.2 Research Framework and Scope

To address the identified problem described above, this research framework and scope are outlined as follows:

1.2.1 Research Objective

Since digitalization is central to the effective industrialization of AM, the initial focus of the thesis was to understand the key digitalization aspects in the design phase that impact the industrial adoption of AM. As the research progressed, the scope narrowed to focus on supporting the suitability analysis of AM during the early design phase, which significantly influences the subsequent stages of the design process. Therefore,

The objective of this thesis is to clarify how to facilitate suitability analysis of AM in the early design phase. Further, to propose a method that assists such an analysis.

This is especially relevant when the comparison between AM and other manufacturing processes is unclear. The hypothesis is that a comprehensive approach supporting such decisions can make the design process more efficient and effective, leading to the appropriate adoption of AM. This is based on the assumption that designers, manufacturing engineers, and end users collaborate closely.

In this thesis, the terms "early design phase" and "pre-conceptual design phase" are used interchangeably to describe the design phase taking place before the development of different design concepts. Additionally, the terms "suitability analysis of AM" and "comparison of AM with CM" are used interchangeably, even though the comparison of these technologies is one of the means to assess the suitability of AM.

1.2.2 Expected Results and Contributions

To satisfy the objective, the intention is to understand the key digitalisation aspects impacting DfAM. In line with this, the next step is to focus on exploring how current methods and tools support manufacturing process decisions in the early design phase, particularly when supporting the comparison of AM with CM methods. This helps to recognise the gaps in literature and common practices. Further, through collaboration with industrial partners, the intention is to identify the critical factors that need to be considered when assessing the suitability of AM for product design and manufacturing in the early design phase. Based on the identified factors, a decision support method is defined to assist engineers in such assessment.

The research presented in this thesis seeks to lower the barriers to appropriate adoption of AM by the following means:

- **From the scientific perspective:** In the literature, the proportion of research studies focused on design aspects of additive manufacturing is significantly lower than the number of studies of materials and manufacturing aspects of AM. Among design studies available, only a small number address the suitability of AM for manufacturing specific products, which is critical for its broader industrial adoption. This research emphasizes the importance of design-focused studies and leveraging available information and data to enhance the integration of AM into industrial practices.

- **From the industrial perspective:** This research raises awareness of the critical data and information that should be considered when assessing the suitability of AM in practice. Further, it provides guidelines to assist the industry in systematically supporting such assessments. In the long term, raising awareness in this field can reduce barriers to the "appropriate" adoption of AM, promoting more informed, data-driven decision-making that integrates AM seamlessly into the design and manufacturing processes.

Figure 1.2 illustrates the relationship between the aim, objective, expected outcomes, and contributions of this research. In this thesis, the **aim** represents the overarching vision or long-term objective, which extends beyond the immediate scope of the current work. It reflects the broader impact that the research ultimately seeks to contribute to, even if not fully realized within this research. On the other hand, the **Research objective** is more focused and specific to what the current research intends to achieve. The **expected outcomes** are a list of the outputs generated through the research, aligned with the research objective. Finally, the **expected contributions** describe how research outcomes advance the larger aim, helping to move closer to the broader vision set by the research.

1.2.3 Research Questions

The following RQs are defined to guide this research in achieving the defined goal:

- **RQ1:** What digitalisation aspects in the design phase are essential to consider for advancing the industrialisation of AM?

- **RQ2:** What are the existing methods and tools, along with their capabilities and limitations, that can assist in determining the suitability of AM during the pre-conceptual design phase?

- **RQ3:** How can the feasibility and suitability analysis of AM be facilitated during the pre-conceptual design phase?

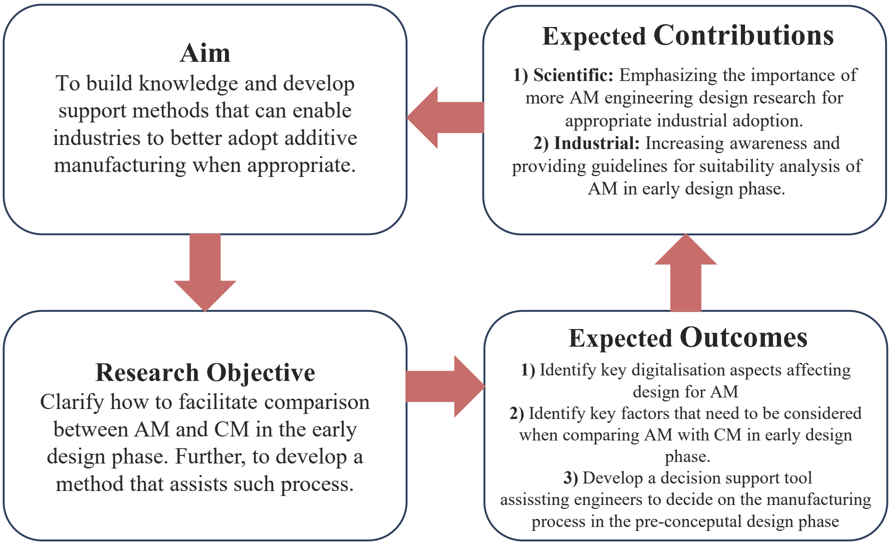

Figure 1.2: Overview of the research aim and delivery in correlation to the main aim and contribution.

- **RQ4:** What role does a prototype tool play in supporting the decision on suitability analysis of AM?

Figure 1.3 illustrates how different research questions are related. In RQ1 the digital aspects in design affecting the industrialisation of AM are identified. While in RQ2 the gaps in available methods and tools assisting suitability analysis of AM are identified forming the foundation for developing a decision support method which is addressed in RQ3. Finally, the importance of developing a prototype tool based on the proposed method is explained in RQ4.

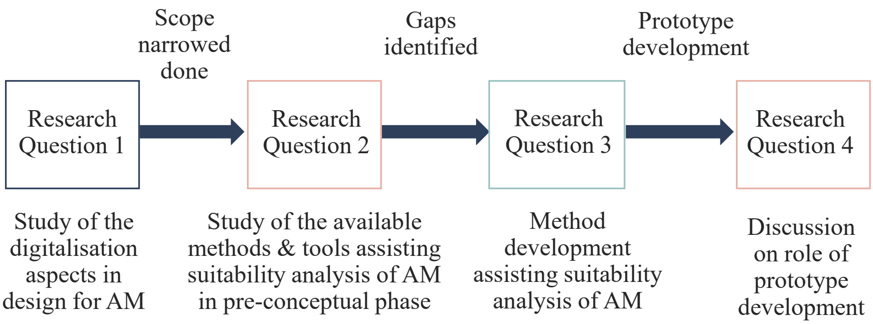

Figure 1.3: Interconnections between the different research questions.

1.2.4 Research Scope and Limitations

In this research, the focus is on scenarios where the comparison between AM and other manufacturing processes is complex or difficult to evaluate. Specifically, the study concentrates on the early design phase where the detailed geometry of the product is not yet defined, making it a suitable phase for assessing the suitability of AM.

This research specifically focuses on the early design phase related to manufacturing process selection and does not address other phases of the design process, stages of product development, or aspects of the value chain. While these areas are relevant to manufacturing decision-making, their influence is only acknowledged in the context of process selection. This study does not aim to modify or directly impact these later phases, which therefore fall outside its scope. In addition, long-term business strategies, such as investments in AM facilities fall outside the scope of this study.

This study was conducted over two and a half years, with several industrial partners involved, though most of the research was carried out in collaboration with one Swedish Original Equipment Manufacturer (OEM). The limited duration of the projects imposed further constraints. In parallel to the work reported here, preparatory studies on how to use AI as decision support have been investigated (e.g. Rad et al. (2024)), yet not included in the thesis, but anticipated to be treated in the further work to PhD.

The overall limitations of the research have been discussed here, while specific limitations of the developed decision support tool are detailed in Section 5.3.

1.3 Thesis Structure

In Chapter 2 the research approach is presented followed by Chapter 3 describing the background and state of the art. Chapter 4 includes a summary of the appended papers, a critical discussion on the findings is presented in Chapter 5 followed by the conclusion and future work in Chapter 6. References and papers are appended at the end.

Chapter 2

Research Approach

This chapter begins with a brief introduction to methodologies in engineering design research in Section 2.1, followed by a detailed description of the methodology employed in this research in Section 2.2. Sections 2.3 to 2.5 then describe the steps taken within the framework of the chosen methodology to achieve the research objective.

2.1 Research Methodology in Design

Design can be defined as the conception and planning of an artifact (Simon, 1996). Or alternatively "*an interplay between what we want and how we want to achieve it*" (Suh, 1990). Research can be defined as the "*Systematic investigation or inquiry aimed at contributing to the knowledge of a theory, topic, etc., by careful consideration, observation, or study of a subject.*"(Oxford University Press, n.d.). Therefore, design research is the attempt to study design phenomena in a scientific manner and to systematically develop and evaluate interventions for improvement or renewal (Eckert et al., 2003).

A methodology is defined as "a system of explicit rules and procedures on which research is based and against which claims for knowledge are evaluated" (Frankfort-Nachmias and Nachmias, 2007). Therefore, a design research methodology helps to systematically structure design research, making it communicable and testable. Design mainly deals with problem-solving. It is interdisciplinary and iterative in nature (Gericke and Blessing, 2012) which is why traditional research methodologies often fall short or require adoption for use in design research. Compared to other fields, there are relatively few research methodologies specifically tailored to design (Reich, 1995).

One of the early design research methodologies was proposed by Antonsson, 1987, who proposed the use of scientific methods in design research. He proposed a six-step approach: 1) Hypothesize that a given set of design rules would explain some aspects of the design process 2) Generate such rules 3)

Train novice designers to apply them 4)Measure their productivity 5) Analyse the results to confirm or reject the hypothesis 6) Revise the hypothesis. He emphasises that the actual hypothesis formulation requires exploratory research and the proposed steps are not necessarily carried in a linear fashion. This methodology highlights the importance of hypothesis creation and testing in the design research paradigm which according to Antonsson is usually neglected.

About a decade later, Duffy and O'Donnell (Duffy and O'Donnell, 1999) proposed another widely known design research methodology The methodology consists of six steps, starting with formulating a research problem, emphasizing that apart from experience, the research problem should be firmly grounded in the literature. A hypothesis is then formulated that leads to the research question and potential solution development. The solution is then formally evaluated with, in many cases, additional industrial user feedback after the documentation of results. While this process gives a comprehensive model for design research, it is noteworthy that the methodology lacks detailed description, in addition to lacking enough explanation of iteration as one of the important elements of design.

Design Research Methodology (DRM) first published in 1992 (Blessing et al., 1992) with the main focus on making design research more scientifically sound. DRM intends to make design research more effective and efficient through a more rigorous approach (Blessing and Chakrabarti, 2009). The framework of DRM is illustrated in Figure 2.1.

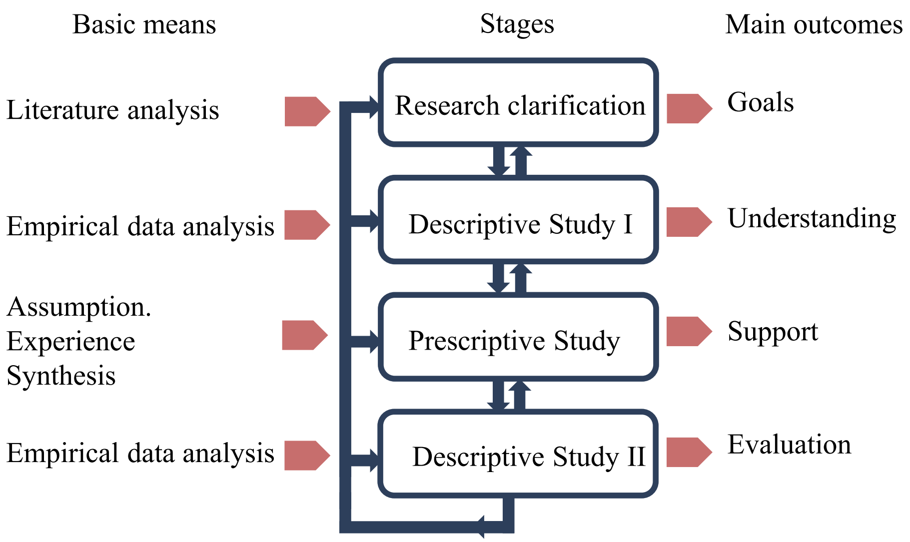

Figure 2.1: The four stages of the DRM framework. Reproduced from Blessing and Chakrabarti, 2009, p 39.

The **Research Clarification (RC)** stage involves formulating a realistic and worthwhile research goal through finding evidence and indications. This stage heavily relies on a literature review to understand the current situation and envision the desired situation. With a clear goal formulation, the **Descriptive Study I (DSI)** deepens the understanding of the current situation through extensive and detailed literature review, as well as industrial observations and interviews. Based on the information collected, a **Prescriptive Study (PS)** focuses on designing design support that intends to bridge the gap between the current and desired situation. As the final stage, **Descriptive Study II (DSII)**, evaluates the design support through empirical studies assessing both applicability and usefulness with respect to the identified research goal. It is important to note that this process is not linear; it involves many rounds of iterations and parallel executions. The starting point does not necessarily need to be the research clarification, nor does a research project need to cover all stages.

2.2 Research Methodology Used

Design Research Methodology (DRM) was chosen as the methodology guiding the following research for the following purposes:

1. It offers both high-level and detailed guidance for conducting design research in a scientifically sound manner. It provides various methods and tools at different stages of the methodology in a coherent way; ensuring that the research is carried out systematically while aligning with the research goal and aim.

2. It facilitates conducting systematic research, at the same time, it provides enough flexibility allowing creativity and innovation.

3. Most of the available design research methodologies, primarily focus on knowledge creation rather than going one step ahead and providing practical implementation guidelines (as also highlighted in the DRM book (Blessing and Chakrabarti, 2009). However, the purpose of conducting design research is to gain a deeper understanding of the process with the purpose of improving it (Eckert et al., 2003). In this respect, DRM stands out from other methods by offering clear guidelines on developing design support (in PS) and testing it through empirical studies (in DSII). Hence, it is well-suited to the current thesis, where the objective is to develop a design support method.

4. It has been tested and refined through numerous design research PhD projects, making it compatible with the context of this research.

As stated in the introduction, the objective of the research is to explore suitability analysis of AM in the early design phase. Further to develop a method that assists such a process. Figure 2.2 shows how different steps are designed based on different DRM steps to satisfy the objective. Note that even though the Descriptive Study II is planned, not yet fully conducted, and therefore excluded from this thesis. Details based on the research context are described in the next section.

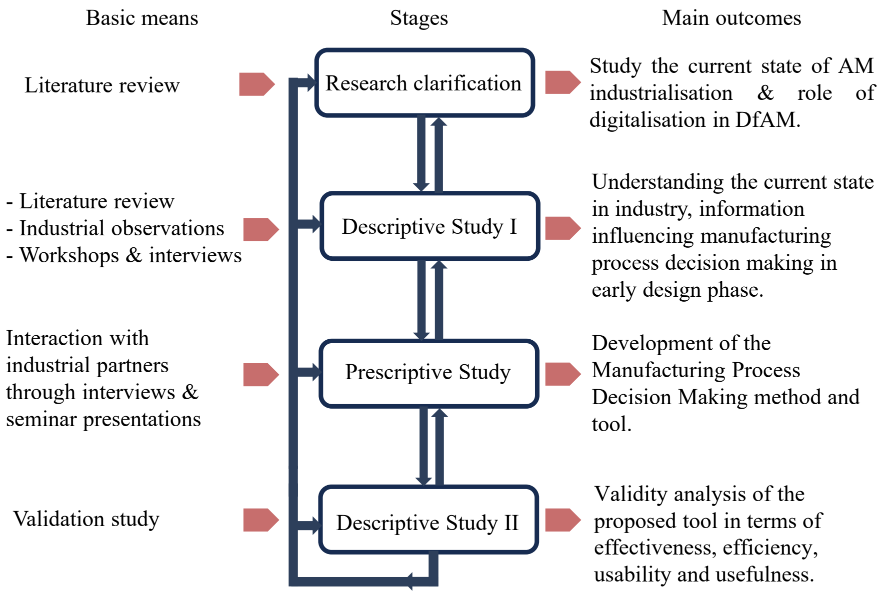

Figure 2.2: Thesis structure in context of DRM Blessing and Chakrabarti, 2009, p 39.

2.2.1 Research Context

This research is based on the action Research Approach (Avison et al., 1999), i.e. industrial collaboration and close engagement with practitioners play a major role in this study. It began with the **DiDAM** project, where the objective of the project was to investigate the important role of digitalisation in the industrial adoption of AM. This project involved six large manufacturing companies, three digital platform providers, and two research institutions, including Chalmers (see Isaksson et al. (2024) and Vinnova (2023)). Among the main three demonstrators defined in the project, this research centres on one conducted in collaboration with a large Swedish construction equipment manufacturer. This company primarily produces high-volume heavy vehicles, which initially may not appear ideal for AM applications. However, there are low-volume, customized products used in daily operations, such as production line tools, that present strong use cases for AM. These products were chosen as suitable case studies for this project.

The partner company aimed to explore how digitalization could support AM adoption, particularly in the design phase. Through several factory visits, workshops, and interviews with designers and engineers, it became clear that systematically capturing and utilizing data across the value chain is essential to assess AM suitability for product design and manufacturing. A detailed map of the production tool order-to-delivery process flow was developed to identify key factors impacting AM suitability analysis in the early design phase. Based on the identified needs and identified key factors, a method was developed to systematically guide AM suitability analysis at this stage.

In addition to DiDAM, other research projects with industrial partners contributed valuable insights. For example, the **Mater-AM** project analyzed the supply chain perspective of the suitability of AM, significantly enhancing the understanding of the business viability of AM in industrial settings. Three major manufacturing companies contributed to the project. In contrast to DiDAM in which interaction with design engineers was the focus, here the supply chain managers and team leaders were the main participants. Additionally, several providers of AM suitability analysis software demonstrated their tools, which significantly contributed to advancing this research. The **DSIP** project further broadened perspectives on sustainability considerations for the design phase, and in **Tolk AI**, the role of AI and ML techniques to enhance early-stage manufacturing process decisions were explored, findings that will be included in the final PhD dissertation. Knowledge gained throughout the research up to this point has also contributed to **AM-EDIH**, a project that provides Small and Medium-sized Enterprises (SME)s with essential digitalisation insights for the successful adoption of AM. This project involves ongoing video production and SME interactions. Figure 2.3 provides an overview of the projects including an approximate timeline.

2.2.2 Correlation of DRM Steps, RQs and Appended Papers

The results of this effort are documented in the four appended papers. Figure 2.4 shows the correlation between the research questions, DRM stages and the appended papers.
Below is a brief description of the papers:

Paper A: *"The Role of Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing"* This paper covers a systematic literature review of existing DfAM methods and tools with respect to digitalisation consideration, as one of the critical factors of AM industrialisation. Further, results of an industrial DfAM case study were presented to explore practical implications concerning digitalisation.

Paper B: *"Information Flow Analysis Enabling the Introduction of Additive Manufacturing for Production Tools- Insights from an Industrial Case"* This paper details the results of an industrial case study in which the information flow of the existing order to delivery information flow of manufacturing products was investigated. Moreover,

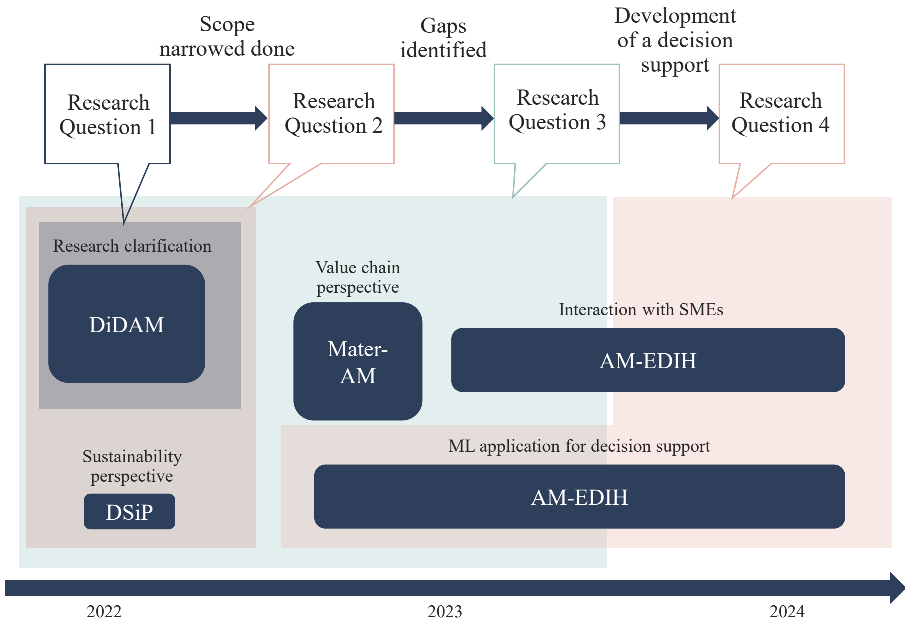

Figure 2.3: Contribution and timeline of different projects with respect to research questions investigation, please note that the duration of each project here indicates the contribution of the project in the current research not indicating the entire project duration.

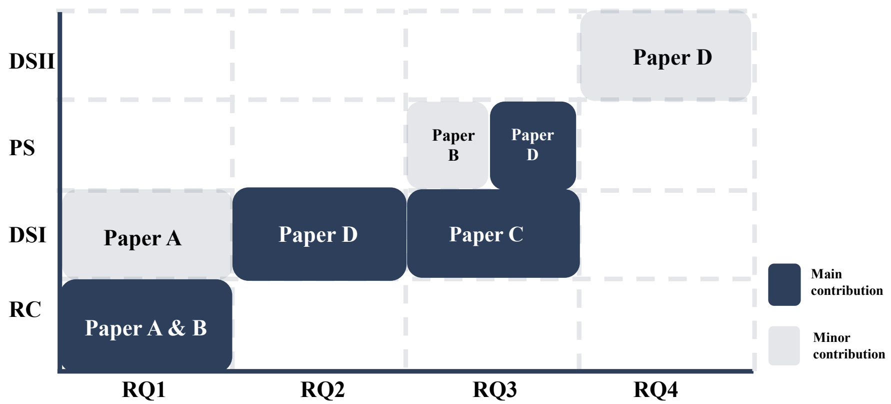

Figure 2.4: Correlation of various RQs with DRM stages and appended papers. The sizes of the rectangular shapes have no significance.

it was investigated how the addition of AM would influence such a process. This paper further highlights the important elements that need to be considered in manufacturing process decision-making in the pre-conceptual design phase.

Paper C: *"Sustainability Implications of Using Additive Manufacturing for Production Tool Design"* This paper focuses on the sustainability implications of AM and investigates the role of digitalisation in sustainable AM production. It highlights the sustainability aspects of AM that need to be considered during the pre-conceptual design phase.

Paper D: *"A Decision Support Tool for Feasibility and Suitability Analysis of Additive Manufacturing in Pre-Conceptual Design Phase"* In this paper key influencing factors affecting suitability analysis of AM are explored. Furthermore, Manufacturing Process Decision Support (MPDS) is introduced as a method that incorporates the identified factors to assess the suitability of AM for manufacturing a part.

2.3 Methods of Data Collection

Two main data collection methods were employed in this research. State of the art data collection is explained in Section 2.3.1 while Section 2.3.2 explains the data collection approach for current industry practices.

2.3.1 State of the Art – Data Collection

During the Research Clarification stage, a general literature review was conducted on studies addressing the pros and cons of AM, the current state of industrial adoption of AM and the barriers to its adoption. Moreover, digital tools used for AM practices and their role in facilitating the industrialisation of AM were reviewed. A general literature review of the design for AM was also conducted. A systematic literature review was performed to understand how different DfAM methods and tools consider digitalisation as a critical element for the industrialisation of AM. The intention of this comprehensive review was to gain a better understanding of AM processes, related aspects and the current industrial state to identify what is hindering the wider adoption of AM.

As part of the Descriptive Study I, an extensive literature review was conducted to gain a comprehensive view of the available manufacturing process selection methods traditionally used, as well as more modern ones comparing AM with CM, and those comparing different AM processes. A combination of systematic literature review and snowballing was used for this purpose. The intention was to investigate whether the available methods can be applied in the early design phase and what limitations they may possess. This was done in parallel with industrial need observations.

Both the systematic literature review processes in the thesis followed a clear guideline on how to search for relevant papers, which criteria to look for in the papers and how to analyse the articles (Kitchenham and Charters, 2007). Multiple datasheets were utilized to gather key elements for each paper, ensuring transparency and making the information easily accessible.

2.3.2 State of the Practice – Data Collection

Interviews played an important role in data collection. Besides the literature review, the majority of data was gathered through interviews. The primary subjects of these interviews were three different plants of the case company in the DiDAM project, while the other two provided complementary insights, ensuring both the credibility and comprehensiveness of the captured information. Both factory visits and online sessions were conducted during the study. All the interviews were conducted in a semi-structured format (Robson, 2002). This approach was chosen because it allowed predefined questions while providing the flexibility for follow-up questions and discussions not covered initially. Data were mainly collected through notes, except where recording permission was granted.

Interviews were carried out in two stages. In the first stage, in Research Clarification and Descriptive Study I, the objective was to understand the current state and needs, presented in the first column in Table 2.1). While later during the PS, inputs from industrial partners were gathered to develop and refine the proposed decision support method (MPDS) presented in the second column of Table 2.1. A total of 25 interviews were conducted, lasting between 30 and 120 minutes, and involved primarily design engineers, manufacturing engineers, line managers, Product Lifecycle Management (PLM) specialists, and end users.

During the Descriptive Study I, four workshops were held involving key actors in the DiDAM case study for three main purposes: 1) Identify important criteria to capture for designing the case study product according to the company perspective 2) Capture the ecosystem around the design phase, specifically how different steps in the value chain influence the design phase, and 3) Determine what needs to be captured for DfAM and how to design a product accordingly.

Table 2.1: Details of the state of practice data collection

A) Understanding the current value chain	**B) Designing the decision support and feedback loops**
Five semi-structured interviews and two workshops with design engineers.	Five semi-structured interviews with one engineering designer.
Five semi-structured interviews with end users.	Two semi-structured interviews with another engineering designer.
Two semi-structured interviews with manufacturing engineers.	One semi-structured interview with a manufacturing engineer.
Two semi-structured interviews with line managers.	Presentation of the tool in two seminars related to the funded project and received feedback for further improvements.
One semi-structured interview with a safety manager.	
Two semi-structured interviews with PLM specialists.	
Two workshops with the innovation manager, design engineer, end users, and manufacturing engineer.	
Two sessions with one designer, an innovation manager, and one end user.	

2.4 Method and Prototype Development

The MPDS method was developed in close collaboration with the case company involved in the DiDAM project, with valuable feedback provided throughout the process for further improvements. A prototype tool based on the method was created initially in the form of an Excel sheet, where initial gaps were identified, and data and information needs were analyzed. Through interviews, further insights were gathered, enabling the organization of these factors into a decision framework that allows information and data to be processed and managed, through user inputs, guidelines and predefined rules. The prototype evolved from a basic interface in Python to a more user-friendly design in Figma. Final inputs from design engineers led to the creation of the tool in PowerApps, consolidating essential aspects for the pre-conceptual assessment of AM suitability into a single context as a decision support prototype. The latest version underwent multiple iterations for further enhancements.

2.5 Research Validity and Reliability

Assessing research validity and reliability is essential, as these two criteria are fundamental to ensuring the quality of scientific research (Carmines and Zeller, 1979). A common definition for validity is the extent to which the research achieved what it was intended to accomplish. Pressman, 2005 states "Every program does something right, it just may not be the thing that we want it to do". This is regarding software engineering but is also applicable in design research. Reliability, on the other hand, refers to the consistency of the results; whether the same results are yielded if the test is repeated (Creswell, 2014). The research aim determines the type of validation and reliability study required (Blessing and Chakrabarti, 2009).

In engineering design, validation involves addressing the dual nature of research contributions: to both knowledge and practice (Isaksson et al., 2020). Contribution to practice is validated in the targeted practical context, whereas validation of knowledge contributions is based on the degree of novelty and alignment with existing scientific literature. These aspects can sometimes overlap, as practical insights and theoretical advancements are often generated within the same studies.

In this research, validity is measured by determining whether the research addressed the "right thing". Whereas, reliability in this context is about ensuring that the research was conducted in the right way (doing "things right").

In terms of validity, the need for a decision support tool in the DiDAM project was initially raised by the designers. Additionally, other industrial projects, particularly MATER-AM, emphasized the importance of a tool to assist in selecting products suitable for the AM process. In the literature, well-known DfAM guidelines, such as those by Diegel et al., 2019, stress the importance of ensuring that AM is the appropriate manufacturing process before proceeding with the design phase. However, few studies focus on the suitability analysis of AM, with most highlighting the need for further research in this area. Therefore, both industrial observations and literature reviews confirmed the need for deeper investigation in the studied area of research. Furthermore, several discussions with senior researchers enforced the importance of this topic. To ensure reliability, the main industrial partners were actively involved throughout the process. It includes collaboration in case studies such as value chain information analysis and developing the decision support framework. Results were either co-developed with the industrial partner or shared with them for feedback and further improvements.

The final version of the decision support, however, was not tested directly with the industrial partners due to the project time constraints. Instead, a small experiment was conducted involving three researchers internally at Chalmers to evaluate the software in terms of efficiency, usability and usefulness. This experiment will form part of a larger validation study and is therefore excluded from the current thesis, it will be provided in detail for the final PhD dissertation.

Chapter 3

Literature Framework

The objective of this thesis is to study the digitalisation aspects that influence design for Additive Manufacturing and, in line with this, to develop a method that facilitates the comparison between AM and CM during the early design phase. To achieve this, the relevant literature and the state of the art are reviewed in this section. Section 3.1 defines AM and highlights its differences from CM processes. Section 3.2 discusses the role of digitalization in the industrial adoption of AM. In Section 3.3, the significance of the design phase is explained, emphasizing its impact on the manufacturing of a product. In Section 3.4 decision-making principles are explained, laying the foundation for investigating state of the art in manufacturing process selection in Section 3.5. Sustainability, as a key factor in choosing a manufacturing process, is addressed in Section 3.6. Finally, the gaps identified in comparing different manufacturing processes (AM vs. CM) in the early design phase, based on insights from these sections are summarized in Section 3.7. Figure 3.1 illustrates the foundation of this research, showing the corresponding sections and their logical relationships, which structure this chapter.

3.1 Additive Manufacturing (AM)

AM is a central topic in this thesis. Therefore, it is relevant to introduce the various technologies within this category and explain their strengths and limitations.

3.1.1 AM Definition and Varieties

AM is a family of technologies that successively join material to create a physical product based on 3D model data. These technologies can be used in various applications such as engineering industry, medicine, architecture, education and more. ISO/ASTM 52900:2021 defines seven categories for AM: 1) Binder Jetting (BJT) 2) Directed Energy Deposition (DED) 3) Material Extrusion (MEX) 4) Material Jetting (MJT) 5) Powder Bed Fusion (PBF) 6)

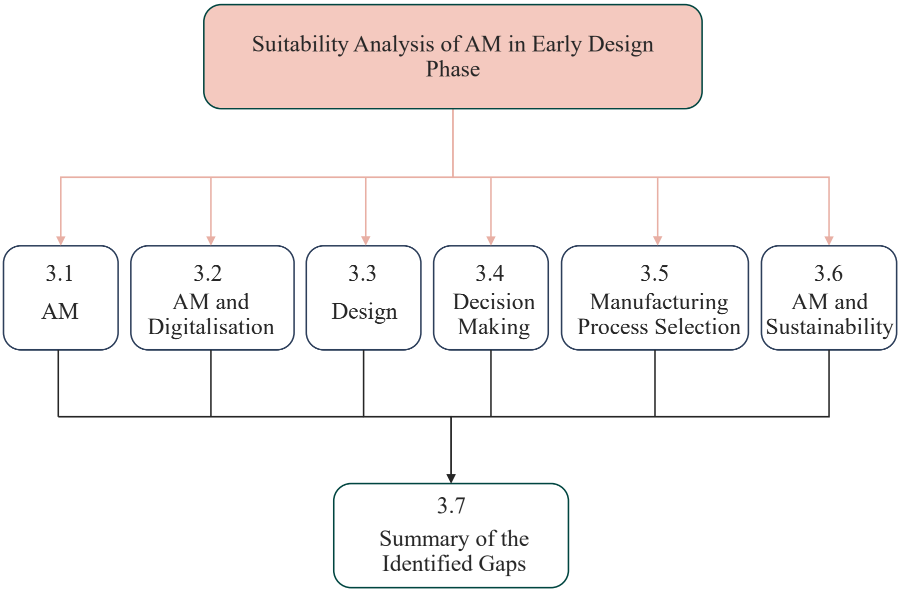

Figure 3.1: Overview of sections and their logical relationships that structure this chapter.

Sheet Lamination (SHL) 7) Vat Photopolymerisation (VPP). These processes are briefly described in Table 3.1. Depending on the category, polymer, metal or ceramics in the form of powder, solid or liquid can be used as the material feedstock.

In 1951 Otto John Munz registered a patent including fundamental elements of what would later become known as VPP technology (Diegel et al., 2019). Until the late 1980s, several patents related to VPP and PBF were registered around the world (including the United States, Japan and France)(Despeisse et al., 2024). However, the first commercial AM machine appeared in 1988 by the company 3D Systems founded by Charles Hull following Hull's registration of a VPP patent in the United States. Since then, with new systems, technologies and materials emerging annually, the landscape of AM has rapidly evolved (Diegel et al., 2019). The continuous advancements in AM have led to its widespread adoption across various sectors, including aerospace, automotive, and healthcare, where it has significantly enhanced manufacturing capabilities (Gibson et al., 2021).

AM has a high innovation rate, with advancements occurring across several dimensions, primarily in terms of material, machine and technology. Thus, manufacturing companies are constantly faced with a broad range of AM technologies and services, forcing them to evaluate a complex set of factors to make informed investment and adoption strategies.

Table 3.1: Different AM process categories based on "ISO/ASTM 52900:2021(en) Additive manufacturing — General principles — Fundamentals and vocabulary", 2021.

#	**Process**	**Short description**	**Feedstock material**	**Material state**
1	Binder Jetting (BJT)	A process in which a liquid bonding agent is selectively deposited to join powder particles.	Polymer/ Metal/ Ceramic	Liquid + Powder
2	Directed Energy Deposition (DED)	A process in which material is selectively deposited and melted by a thermal energy source concurrently.	Metal	Solid (Filament/ Powder)
3	Material Extrusion (MEX)	A process in which material is selectively dispensed through a nozzle or orifice.	Polymer	Solid (Filament)
4	Material Jetting (MJT)	A process in which droplets of feedstock material are selectively deposited and solidified.	Polymer	Liquid (Suspension)
5	Powder Bed Fusion (PBF)	A process in which thermal energy selectively melts regions of a powder bed.	Polymer/ Metal/ Ceramic	Solid (Powder)
6	Sheet Lamination (SHL)	A process in which sheets of material are bonded to form a part.	Polymer/ Metal	Solid (Sheet)
7	Vat Photopolymerisation (VPP)	A process in which liquid photopolymer is selectively cured by light-activated polymerization.	Polymer	Liquid (Suspension)

3.1.2 Strengths and Limitations of AM

To distinguish Additive Manufacturing (AM) from other manufacturing processes, the term Conventional Manufacturing (CM) is used to refer to traditional manufacturing processes including subtracting methods, casting and forming (Gibson et al., 2021). AM is fundamentally different from other manufacturing methods, both in terms of the manufacturing process itself but also the value chain and ecosystem surrounding it. Therefore, to fully understand the strengths and weaknesses of AM, it is essential to assess it from both the manufacturing process and value chain perspective.

Process Perspective:

In the majority of cases, AM is more material-efficient as in the process material is usually added where needed in contrast to the majority of CM methods where the material is subtracted from a bulk. This opportunity allows the production of customised and complex products (Ford and Despeisse, 2016). This is a relatively important aspect as not only more material is saved but also products can be less heavy without compromising quality. In CM, increasing the complexity of a product often requires more tooling (and sometimes designing the tool itself), which can add to the process complexity, lead time, and cost.. Complex and customised products can be manufactured by AM without any extra cost or additional tooling requirement (Gibson et al., 2021). Further, AM process is more controllable and flexible, for instance, different lattice structures or different materials can be used within various parts of the product in case of value proposition (Raffaeli et al., 2021).

While AM is a practical and efficient prototyping technique, it is generally considered a slower and often more energy-intensive process compared to CM for manufacturing end products (Despeisse et al., 2024). Combined with high investment cost, this makes AM a more expensive option in comparison. Therefore, AM is usually most suitable for manufacturing low-volume and customised products (Mellor et al., 2014). Also, there are concerns regarding the quality of the products manufactured by AM in terms of consistency and the need for post-processing. Often new quality assurance and control procedures need to be defined for AM parts. Despite ongoing efforts in AM material development, the range of suitable materials for AM remains limited in comparison to CM processes. Further, certain AM technologies are limited to the dimensions of the build chamber, limiting the product feasible dimensions (Verma et al., 2022; Ahuja et al., 2015).

Value Chain Perspective:

AM offers distinct advantages over CM from value chain perspective. The process steps are significantly reduced, as once the product is designed, it can be directly sent to the AM machine for manufacturing. The complexity of the product does not add any additional steps in contrast to CM (Gibson et al.,

Table 3.2: Summary of strengths and limitations of AM

AM Strength	AM Limitations
Material efficiency	Usually more expensive than CM
Customised/complex products	Usually significantly slower than CM
Possibility of using different materials or lattice structures in same part	Energy intense process
Part consolidation (simplified assembly)	Less material options compared to CM
Simplified supply chain	Product dimension limited to the build chamber (in case of any)
Possibility of print on distance	Uncertainties and issues if printed on distance (such as quality assurance and data security)
Possibility of print on demand	Usually post-processing is needed to improve surface finish or mechanical properties

2021). Further, more design freedom in AM allows part consolidation, leading to reducing assembly steps (Ngo et al., 2018; Kunovjanek et al., 2022). In the AM process, the 3D CAD model should be directly sent to the AM machine to print with no extra steps in between, therefore product can be manufactured remotely. This can potentially reduce lead time and cost, particularly for products that need to be delivered to distanced or remote locations (Chiu and Lin, 2016). Moreover, as products can be produced on demand, physical inventories can be replaced by digital inventories.

Despite these significant benefits, several challenges exist with regard to supply chain implications of AM. For instance, data protection issues arise when a 3D CAD model is sent to a distanced location. Ensuring the product is manufactured as intended, not modified or duplicated poses a significant challenge (Adkins et al., 2021; Isaksson et al., 2024). In addition, quality assurance is a major concern. When a 3D CAD model is sent externally for print, questions arise about the product quality assurance and the responsible party. This becomes more complicated as most AM manufactured products (especially metals) require post-processing to improve surface finish or increase product mechanical properties by heat treatment (Gao et al., 2015). Table 3.2 Summarises the strengths and limitations of AM.

AM thus has both strengths and weaknesses when it comes to the manufacturing process itself but also the value chain perspective. As a result, the applicability of AM is highly case-dependent, and it is difficult to establish a universal rule to generalize its suitability.

3.2 AM and Digitalisation

The Industry 4.0 paradigm has introduced a new era of manufacturing with digitalisation at its core (Xu et al., 2021), characterized by data-driven advancements in manufacturing systems, such as smart factories and cyber-physical systems through IoT, AI, simulation techniques, and robotics (Lasi et al., 2014; Khorasani et al., 2022). As a key component of Industry 4.0, AM is uniquely positioned within this framework, with product digital models directly sent to printing machines for automated production (Diegel et al., 2019). For successful industrial adoption of AM not only does suitable digital infrastructure need to be in place, but also the AM process needs to be adapted to the existing ecosystem (Gericke et al., 2020; Tian et al., 2022).

In this section, the key digitalisation aspects affecting the adoption of AM are briefly addressed. Starting with digital compliance, data format compatibility is essential to enable smooth integration across systems, which is often hindered by varying data formats from different vendors. Standards such as ISO 10303-242 ("ISO 10303-242:2022 Industrial automation systems and integration—Product data representation and exchange—Part 242: Application protocol: Managed model-based 3D engineering", 2022) provide guidelines, but still, more effort is required as both digitalisation and AM are constantly under development. Seamless data exchange and standards must be established to reduce the risk of data flow disruption, particularly in distributed manufacturing environments, where compatibility between systems and formats is critical (Isaksson et al., 2024).

Digital control in AM involves the operation and real-time monitoring of production processes, integrating automated systems such as robotics to manage the manufacturing and inspection process. Process control enables fine-tuning of AM processes, ensuring the quality of the manufactured product.

In digital management, the focus is on tracking and managing information and data throughout the AM process. This aspect is especially important in complex supply chains. Digital thread plays a significant role in this case, allowing for traceability and effective data transparency. PLM for instance can be used to improve the manufacturing process by improving traceability and monitoring at each stage of the product lifecycle (Mies et al., 2016; Bonham et al., 2020).

Digital accuracy and prediction capabilities are important as AM relies on highly detailed digital representations of products and processes. Data-driven approaches enable continuous performance improvements and support the early identification of potential defects or failures, significantly enhancing process reliability and efficiency (Jiang et al., 2022). For instance, integrating digital twins, AM processes benefit from advanced simulations that predict potential issues, optimize parameters, and reduce downtime, ultimately improving both product quality and production efficiency (Knapp et al., 2017). AI-driven simulations can further optimize AM processes, fine-tuning parameters to reduce material and energy consumption while maintaining product quality (Majeed et al., 2021).

Digital security is a growing concern in AM application, given the data-intensive nature of this process. Intellectual Property concerns, particularly when collaborating with external actors, require robust data security measures to prevent data theft and unauthorized access to sensitive information. Establishing secure data exchange flows, however, ideally should not impose excessive administrative burdens (Ballardini, 2019).

Despite the considerable importance of integrating digital aspects in AM process infrastructure, challenges remain. Industry often underestimates the impact of such consideration in the adoption of AM (Isaksson et al., 2024). Further, lack of skill and issues with knowledge management can act as barriers to adopting digitalisation. The specialised skills for AM processes, including digital design, data analytics and cross-functional IT system management, often exceed the capabilities of existing workforces. Additionally, the high costs associated with implementing digital infrastructure, such as advanced simulation and data management software, along with cybersecurity measures, pose financial challenges, especially for SMEs with usually fewer available resources (Martinsuo and Luomaranta, 2018; Jones et al., 2021).

3.3 Design

In this section first, the definition and importance of design in relation to the product supply chain and lifecycle is discussed in Section 3.3.1. Further, the definition of the early (pre-conceptual) design phase used in this research is discussed. In Section 3.3.2, Design for X (DfX) guidelines are explained highlighting the importance of these methods affecting the result of the manufacturing process.

3.3.1 Critical Role of Design and Its Definitions

Design is considered one of the important phases of the supply chain, it not only affect the manufacturing phase but also the entire product lifecycle (Pahl et al., 1996). According to European Commission (n.d.) up to 80% of product environmental impacts are determined in the design phase. Therefore, critical consideration needs to be given to the design phase to achieve optimal outcomes (Ulrich and Eppinger, 2016).

Design is multifaceted and can be defined in various ways (Wynn & Clarkson, 2018). In the realm of engineering design, it is often referred to as a problem-solving activity. For instance Ullman, 2009 provides a generic set of design phases including 1)Product discovery (understanding the need) 2)Project planning (resource planning) 3)Product definition (laying the foundation of the design) 4)Conceptual design (generate different concepts) 5)Product development (refine and finalise the best concept) 6)Product support (such as product documentation, etc.).

Pahl et al., 1996 structure the design process into four main phases: 1) Planning and task clarification 2) Conceptual design 3) Embodiment design, and 4) Detail design. Ulrich and Eppinger (2016) proposed a generic product development process consisting of six steps: 1) Planning 2) Concept development 3) System-Level design 4) Detail design 5) Testing and refinement 6) Production ramp-up. Hubka and Eder (1996) high-level model of the product development process begins with task clarification, where the functions and requirements are identified. This is followed by defining function structures, developing organs or conceptual solutions to address the functions, and subsequently progressing to component structure definition and detailed development.

Most design processes, including those mentioned above, follow a similar pattern: beginning with a detailed understanding of the problem and objective, generating and evaluating various concepts based on the identified requirements, and refining the most suitable concept for testing and eventual manufacturing. In this thesis, the term **pre-conceptual design** or **early design phase** is used to denote the stage in the design process that occurs before the definition of concepts (as described in Hubka and Eder (1996)'s procedural model). This stage focuses on framing design preconditions, establishing criteria, and requirements, identifying constraints, directing the search for solutions and generating various concepts.

Decisions made during this phase have a high impact on the product development process and its lifecycle, making it a crucial phase in the product development process (Pahl et al., 1996). Critical design decisions including product requirements and architecture are made at this stage (Ulrich and Eppinger, 2016). At this step freedom is high and making changes to the design will not cost significantly, therefore the goal is to learn about the product as much as possible at this stage (Ullman, 2009). For instance, determining the product manufacturing process at this step can substantially affect how the product is designed.

However, a key challenge in this phase is the absence of a defined geometry and the majority of the information and data available are unclear and incomplete. Furthermore, experience plays a critical role in this phase, as engineers often think and act based on their existing knowledge. When AM is introduced, a lack of experience may lead to oversight of important aspects, and potentially affect the design process adversely. Therefore, it is crucial to capture, organise and benefit from data generated at this phase to increase the chance of making correct design decisions. As noted by Douglas C. Eddy and Steudel (2019), "realising the right decision too late in a design process will lead to wasted design time, increased time to market the product, a functionally inferior design, and/or a costlier product".

3.3.2 Design for X (DfX)

Design for X (DfX) refers to a set of design guidelines, methods and tools that aim at optimising various aspects of a product lifecycle. The "X" stands for a specific objective. Based on the review conducted by (Kuo et al., 2001), the first structured DfX was Design for Assembly (DfA) in the early 1980s where assembly constraints were considered during the design phase (Boothroyd and Dewhurst, 1983). Considering these constraints can lead to the final cost reduction. Later the concept of Design for Manufacturing (DfM) was developed to emphasize having manufacturing in mind during the design phase with the objective of reducing lead time and cost while meeting the desired quality and reliability (Bakerjian, 1992). Both DfM and DfA led to significant benefits in terms of simplification of products, reduction of cost and time and improvement of quality (Kuo et al., 2001). More recently concerns regarding sustainability have been raised leading to more sustainability-oriented DfX concepts, design for sustainability, design for recyclability and design for circularity are some common examples (Bhamra and Lofthouse, 2008).

DfM is the most relevant DfX guideline in this thesis. According to Bakerjian, 1992 DfM designed products can get to market faster as they fit well into the existing processes and decrease the number of iterations significantly. Considering manufacturing issues early in the process leads to fewer product problems that result in quick and smooth product introduction. Early versions of DfM methods consider CM techniques as AM was not yet introduced to the market. AM has fundamental differences from CM techniques. For instance, printing orientation, overhang angle, and sharpness of the corners are new elements that need to be considered in the design phase which does not exist in regular DfM guidelines. Therefore, when this family of technologies started to become deployed many efforts were put into defining DfAM guidelines (Diegel et al., 2019 published one of the most well-known contributions, see also Rosen (2007), Adam and Zimmer (2014), and Thompson et al. (2016)).

Diegel et al., 2019 encourage engineers and designers to consider strategic benefits and constraints of AM in the early design phase before concentrating on the detailed design. This proactive approach allows potential issues to be identified and addressed early, improving the product design and later stages of the value chain. Moreover, designers are usually hesitant to change designs drastically once the CAD model is ready, as the incurred sunk costs make such changes less appealing (Douglas C. Eddy and Steudel, 2019). As the product designed for AM can be significantly different from the one designed for CM, therefore, it is critical to determine the type of manufacturing process in the pre-conceptual design phase to later apply suitable DfM guidelines (if applicable, DfAM). As stated by Bakerjian, 1992, "by the time a product has been designed, only about 8% of the total product budget has been spent. But by that point, the design has determined 80% of the lifetime cost of the product!".

Design influences manufacturability and that plays a pivotal role in product introduction and production. Despite the critical role of this consideration, most of the available design guidelines for AM are DfAM oriented, meaning providing guidelines on how to optimise a geometry to be suitable for a specific AM process such as optimising overhang angle, part orientation or support structure (Douglas C. Eddy and Steudel, 2019). If any guidelines are provided for the suitability analysis of AM, they tend to be quite general and lack robust data processing and quantification in relevant contexts.

3.4 Decision Making

Human beings are constantly faced with decision-making. Our biases and dysfunctional habits interfered with this process. The brain is not wired to make “good” decisions especially when the situation is unique and uncertainty is high. We are wired to settle for “good enough” which can be distanced from the best choices we can make. This affects personal, societal and business decisions. For couple of centuries, scholars have studied how human make decisions and how to make better decisions (Spetzler et al., 2016).

As explained in the Introduction Chapter, manufacturing process decision-making has increasingly become more complex over time and still, we as humans are responsible for making the right decision. Therefore, it is relevant to study how to incorporate decision-making fundamentals into manufacturing process decision-making.

3.4.1 Fundamentals of Decision Making

Decision theory intends to provide a structural approach for making logical choices when dealing with uncertainty (Parmigiani and Inoue, 2009; Peterson, 2017). There are two main decision theory categories; descriptive decision theory which seeks to explain how people naturally make a decision, whereas in normative decision theory, rational decision making is studied. Decision theories mainly deal with rational decisions rather than the right decisions, since decisions can be rational without being right and vice versa. A decision is considered rational if and only if the decision maker chooses to do what they have most reasons to do at the time of making a decision.

Decision under uncertainty refers to decisions both under ignorance and risk. In decision theory, these terms have individual definitions. Decision under ignorance refers to the cases where the decision maker is aware of the alternatives and the outcomes but is unable to assign any probability to the corresponding outcomes. On the other hand, in a decision under risk probability of the possible outcomes is known(Peterson, 2017).

Decision-making can be complex due to multiple criteria, conflicting objectives and different levels of uncertainty (Keeney and Raiffa, 1993). One of the widely studied methods facilitating this process is Multi-Criteria Decision Making (MCDM) methods. This family of methods seeks to explicitly take into account existing and in most cases conflicting criteria into account while making an important decision. The core idea of these methods is to make the decision-making process rational and transparent (Belton and Stewart, 2012). MCDM consists of three main steps:

1. Identification and selection of the criteria

2. Assigning weights to the criteria based on their importance

3. Identify alternatives and rank them based on a suitable MCDM method.

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy Process (AHP) are among the main MCDM methods. AHP makes a pairwise comparison of criteria, whereas TOPSIS evaluates the distance of different alternatives to the ideal solutions (Taherdoost and Madanchian, 2023).

3.4.2 Decision Making in Product Development

Decision-making is one of the main components of product development processes, as it influences the process from initial task clarification to final product detailed design. In process models such as Ulrich and Eppinger (2016), decisions are integrated at every stage, starting with defining the clear objective and problem formulation. Later, the relevant criteria and requirements need to be specified which guides the development process. The importance of these requirements needs to be determined as they influence subsequent decisions such as concept generation and evaluation. Setting priorities in this case ensures that design efforts focus on the most critical aspects of the product.

As the process advances, concept screening needs to be conducted to narrow down the alternatives. MCDM-based methods such as Pugh controlled convergence (Pugh, 1991) and Kesselring selection method (used in Pahl et al. (1996)) are used for this purpose. These methods help to compare various concepts against each other with respect to fulfilling specified criteria. These methods allow for systematic evaluation and ranking of alternatives, ensuring that the chosen concepts align with the identified priorities. Once a concept is selected, further decisions need to be made during the detailed design phase. This includes detailed design of different components, relevant dimensions, selection of material and manufacturing setup. This requires careful consideration to optimise the product in terms of performance, cost and manufacturability. This emphasizes the ongoing role of decision-making throughout the entire product development process, from the initial stages to the completion.

While classic product development approaches are well-established, they do not directly address or implement digitalisation aspects. More recent advancements in decision-making in product development benefit from digitalisation, at the same time proposing more complex methodologies. Multidisciplinary design optimisation, design space exploration, and data-driven design are some examples (see Gray et al. (2019); Nardi et al. (2019) and Cantamessa et al. (2020)). These methods highlight the need to explore and evaluate various types of information and data systematically to support informed design decisions.

3.4.3 Positioning Manufacturing Process Selection in Decision Making Context

In practice, integration between design and manufacturing processes is often limited, despite the importance of cross-functional collaboration and the existence of practices such as concurrent engineering (Smith, 1997). This separation can hinder collaboration, leading to inefficiencies and challenges in aligning design with manufacturing requirements. However, assuming this integration is achieved, positioning manufacturing process selection within decision theory typically follows a normative approach, aiming for rational decisions that optimize cost, time, and quality. Given the inherent complexity and uncertainty in early design, descriptive elements such as designer intuition and experience are also essential (Pahl et al., 1996).

As explained in 3.3 it is critical to make informed decisions about the type of manufacturing process as early as possible in the design phase. In manufacturing process decision-making within design, available guidelines often depend heavily on designers' experience rather than leveraging available data and information for informed decisions. This reliance on expertise is particularly challenging in AM, where engineers may lack sufficient knowledge of AM and relevant factors required to consider. This gap highlights the need for more effective, data-driven approaches to manufacturing process selection, allowing for improved accuracy and adaptability in AM environments.

Decisions on the suitable manufacturing process can be complex, including multiple criteria with conflicting objectives. Therefore, this decision-making process can benefit from structured decision-making approaches such as MCDM to improve quality and transparency. There are methods available in literature applying MCDM to compare different manufacturing processes, particularly AM and CM. These methods are discussed in detail in a subsection of the following section, as they represent one of the main categories of manufacturing process selection methods covered below.

3.5 Manufacturing Process Selection

The importance of early manufacturing process selection in the design phase has been discussed. This decision can influence the product quality, lead time and cost. Understanding the characteristics and implications of candidate manufacturing processes is essential for making informed decisions. In the case of AM, however, there is often limited information available, along with complex upstream and downstream product life cycle activities.

Highlighting the importance, the following section explores available methods for manufacturing process selection, focusing on their suitability for the pre-conceptual design phase, where detailed geometry is not yet defined. The purpose is twofold: first, to assess to what extent these methods can aid early-phase decision-making, and second, to determine their applicability in comparing AM with CM for a given part. In Section 3.5.1 traditional methods, primarily established before the widespread adoption of AM are elaborated, followed by exploration in Section 3.5.2 of more contemporary methods that take AM into account.

3.5.1 Traditional Manufacturing Process Selection Methods

One of the well-known material selection methods in mechanical design is proposed by Ashby, 2005 that enables eliminating infeasible material options by comparing product requirements with material properties. This method was later extended to define a manufacturing process selection method that links product function and requirements to material and manufacturing constraints, further narrowing down the range of feasible options. This method is commercialized by Granta EduPack ANSYS Inc., 2024 and is widely used in education and practice. Another well-recognized approach is presented in the handbook by Swift and Booker, 2013. They propose the PRIMA selection matrix that relates compatible materials to manufacturing processes, considering product annual production quantity. Essentially, a list of feasible manufacturing processes is generated based on production volume and suitable material. Later in the process, these processes are studied in more detail to be compared against product requirements, further screening out infeasible alternatives.

Another framework is proposed by Lovatt and Shercliff, 1998 consisting of two phases: product objectives and requirements are defined in Phase 1, while technical and economic evaluation is carried out in Phase 2 to screen out infeasible and irrelevant processes. These methodologies follow the same pattern as depicted in Figure 3.2. The process begins with the definition of product objectives and requirements, followed by the elimination of infeasible material and manufacturing options based on the given constraints. Later, the detailed product design is defined which defines the final choice of material and manufacturing process.

These methods are foundational for manufacturing process selection and are effective at eliminating infeasible manufacturing processes to a great extent. However, they leave feasible alternatives to last as long as possible. As stated by Lovatt and Shercliff, 1998 "*... all combinations remain possible until actively excluded.*". Although this approach keeps the design space open, which is beneficial, it limits the potential advantages that can be achieved by using DfX

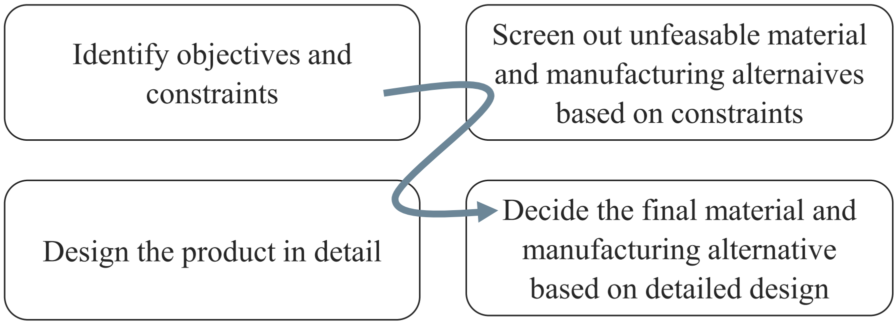

Figure 3.2: Common traditional manufacturing process selection procedure in design phase

guidelines, where the product is specifically tailored to maximize the benefits of the chosen manufacturing process. Further, these traditional methods do not directly address AM and as AM has fundamental differences with other manufacturing methods, these methods need to be updated to be more inclusive. Swift and Booker previously published a manufacturing process guideline (Swift and Booker, 2003) which was later updated to Swift and Booker, 2013 including AM. However, AM is referred to as rapid prototyping technology, providing separate PRIMA matrices distinguished from other manufacturing methods used to produce end products.

3.5.2 Modern Manufacturing Process Selection Methods

When considering AM for design and manufacturing a product, it is critical to recognize the challenges in terms of scaling up, logistics, resource availability, supplier readiness and qualification processes. This necessitates the need to incorporate additional, non-conventional aspects into the assessment process. Recent efforts, therefore, have focused on assessing the feasibility and suitability of AM for producing a product. These efforts can be grouped into two main categories: geometry-based analysis (explained in Section 3.5.2.1) and methods based on MCDM (elaborated in Section 3.5.2.2).

3.5.2.1 Geometry-based Methods

One important category of comparing AM with CM for manufacturing process selection is based on geometry analysis. For instance Ghiasian et al., 2020 introduced an AM feasibility analysis method that evaluates product geometry, providing decision support through technical and economic analysis. Similarly, Tedia and Williams, 2016 analyzed part geometry to evaluate AM manufacturability using voxel-based representations schema. Yang et al., 2020 introduced a decision support framework that assesses AM suitability by analyzing product

CAD models with ML techniques.

There are commercial tools facilitating this process. For example, PrintSyst.ai, n.d. evaluates product geometry based on DfAM guidelines to determine whether a part is printable, and if so, which printing process is the most suitable. Another example CASTOR, 2020 use algorithms to analyse product geometry based on technical and economic perspectives to recommend when it is beneficial to use AM instead of other manufacturing methods. Other geometry based tools include CDS, 2024, 3YOURMIND, 2024, nTop, 2024 and Materialise Magics, 2024. However, these methods often overlook a critical consideration: to maximise the benefit of using a manufacturing process (particularly AM), the part should be specifically designed for that process. Consequently, analysing the product only when the detailed geometry is available may be too late for a comprehensive and informed manufacturing process decision-making.

3.5.2.2 MCDM-based Methods

Another dominant category of manufacturing process comparison is based on MCDM methods. To apply such methods, first, the objectives of manufacturing such a product need to be specified, followed by generating different manufacturing process alternatives (i.e. based on the objectives and constraints including material options). Later, a suitable MCDM method is applied to compare different manufacturing process alternatives against each other to finally select the suitable manufacturing process with the highest rank for the given task.

A literature review by Rai et al., 2022 revealed that the majority of the decision support methods used for AM fall within this category. As an example, the method introduced by Douglas C. Eddy and Steudel, 2019 compares different manufacturing processes (including AM) at the early design phase by evaluating technical and economic criteria. Another example is provided by Ren et al., 2022 who introduced a new MCDM method that incorporates certainty to evaluate and compare various processes to select the most suitable process for a specific part. Zheng et al., 2017 proposed a novel MCDM approach for selecting appropriate AM processes which addresses incomplete information and performance criteria.

Incorporating MCDM methods in manufacturing process decision-making can make the process more transparent and optimise the resource consumption (Madic et al., 2016). When the type of the manufacturing process is defined early in the design phase, suitable DfX guidelines can be applied. This is one of the limitations of methods explained before. Also, these methods incorporate engineering experience into the decision-making process, which makes the method more valuable. However, results can vary significantly depending on who implements the method. Furthermore, they are generally time-consuming and do not offer a systematic guideline for deciding on which criteria to consider. The majority of the methods lack considering the main key factors that affect the manufacturing process decision-making at this stage. For instance, incorporating AM into the manufacturing process portfolio necessitates a thorough review of the product quality assurance procedure. This adds additional costs, which are often not accounted for when deciding on the manufacturing process.

In summary, most traditional and recent manufacturing process selection methods provide valuable frameworks for eliminating infeasible options or ranking alternatives based on various criteria. However, they generally lack consideration of the unique complexities introduced by AM. The absence of suitable guidelines and lack of taking into account some of the key influencing factors presents a gap for further development of more tailored approaches in this regard.

3.6 AM and Sustainability

Concerns regarding sustainability are increasing particularly in the manufacturing sector which accounts for approximately 20 to 30% of the global greenhouse gas emissions (Our World in Data, 2020; Worldmetrics, 2024) that calls for urgent action. As stated previously, up to 80% of the product's environmental impact is determined in the design phase (European Commission, n.d.). In the conceptual design phase, design freedom is high and the cost for change is relatively low which offers a great opportunity to influence product sustainability impact. Thus, it is essential to select a more sustainable manufacturing process against other processes in the conceptual design phase, guiding the product's detailed design based on the process opportunities and constraints(Ramani et al., 2010).

Application of AM is transitioning from solely prototyping to manufacturing of end products. Hence, understanding its sustainability implications is crucial especially in the current transition phase where this technology is not yet fully adopted in industrial sectors (Graziosi et al., 2024).

Assessing the sustainability of AM is significantly challenging and still not fully understood (Hegab et al., 2023). On one hand, numerous studies have concluded that AM processes are more energy-intense than CM methods (Sauerwein et al., 2019). On the other hand, some other studies highlighted that solely focusing on one production phase does not provide a comprehensive understanding of the AM sustainability impact (Majeed et al., 2021). For example, Gebler et al., 2014 demonstrated that when considering the entire product lifecycle, AM has the potential to reduce costs, energy consumption and CO2 emissions. Additionally, AM is known for its ability to shorten the supply chain and minimise material waste, contributing to more sustainable manufacturing practices (Ford and Despeisse, 2016). However, substantial nuance is needed before claiming this. For instance, production of waste highly depends on the product design, material and AM machine. For instance, a design can need a substantial amount of support structure to be printable, which can generate considerable material waste (Graziosi et al., 2024). Thus, the sustainability of AM is highly case-dependent, and it is not straightforward to label this technology universally more or less sustainable than other manufacturing processes (Faludi et al., 2015).

Adding to the complexity of assessing AM sustainability, it is critical to note that sustainability is not only limited to the environmental aspects, social and economic dimensions also need to be considered. These elements, i.e. social, ecological and economic, affect one another, meaning that changes in one element impact other elements (Geissdoerfer et al., 2017; (Mebratu, 1998). Compared to ecological and environmental aspects, the social sustainability implications of AM remain underexplored ((Naghshineh et al., 2021).

It is particularly important to explore and consider these sustainability aspects in the conceptual design phase when comparing different manufacturing processes (e.g. AM versus CM). Markou et al., 2017 proposed a method that integrated environmental considerations into the AM early design phase. While this approach is a promising start, it solely focuses on the environmental factors, not addressing the economic and social aspects. Few studies have investigated comprehensive sustainability assessment of different manufacturing processes in the conceptual design phase which calls for further research.

Therefore, suitable guidelines and tools are needed to be applied in the conceptual design phase to compare different manufacturing processes - especially AM and CM- concerning their sustainability impacts across all three dimensions: Guidelines that can be used to select a manufacturing process with potential less sustainability impact without compromising the product quality. According to the manufacturing process candidate, appropriate DfX guideline can be hence applied.

Both digitalisation and sustainability are among the key trends recently (Hallstedt et al., 2020). However, the intersection between these two areas is underexplored (Despeisse et al., 2022). Further research is required to examine how digitalisation influences sustainability and how it can be leveraged to promote sustainable manufacturing practices. Therefore, more study is needed to investigate first the influence of digitalisation on sustainability, and second how it can be applied to be in favour of sustainable manufacturing.

3.7 Summary of the Identified Gaps

Based on the review of the current state of the art, the research gaps identified in this study are summarized as follows:

1. **AM and digitalisation**: AM and digitalisation are closely connected which is one of the key, often overlooked aspects of AM adoption. Apart from the importance of suitable digital infrastructure for smoother AM adoption, a substantial amount of data and information is generated in AM process, much of this remains underutilized. This is an opportunity

to leverage digital capabilities, especially in the early design phase to enhance the design and manufacturing phase. There have been numerous efforts to implement ML in DfAM to optimise material properties, design and process parameters. Despite these, there is limited research on incorporating ML in the early design phase facilitating manufacturing process decision-making.

2. **AM design research**: As a disruptive technology, AM significantly impacts both product lifecycle and business perspectives, particularly through Design for AM. While substantial progress has been made in developing AM technology and materials, research addressing design-specific topics remains limited.

3. **DfX and Early Process Selection Challenges**: To maximize the benefit of DfX guidelines, the type of manufacturing process should ideally be determined early in the design process. However, current DfX guidelines are typically tailored to specific manufacturing processes, offering design guidance without directly supporting manufacturing process decision-making. Additionally, most available manufacturing process selection methods depend heavily on detailed product geometry, limiting their applicability for guiding early design adjustments.

   In this context, data- and information-driven approaches become crucial. Digitalisation, particularly within the Design for Additive Manufacturing (DfAM), offers the potential to make early process selection more informed and adaptable. By leveraging digital tools and data insights, the approach in this thesis aims to address the challenges of process selection in the early design stages, ensuring alignment with AM-specific needs and lifecycle considerations.

4. **Traditional methods of manufacturing process selection**: Traditional methods for selecting manufacturing processes primarily focus on screening out infeasible options and often defer the final decision on a suitable process until the detailed design is complete. This approach limits the early application of DfX guidelines that could optimise the design for the chosen manufacturing process. Moreover, most established selection methods rely heavily on the experience of the user regarding the manufacturing process capabilities and constraints, a factor that is often lacking for AM. AM introduces unique characteristics and considerations that are not traditionally included in selection methods, largely because these factors are not yet widely recognized as essential.

5. **Recent manufacturing process selection methods**: Recent methods assisting suitability of AM primarily focus on product detailed geometry analysis which cannot be applicable in the pre-conceptual design phase, thereby, restricting the potential advantages of DfX capabilities. Another main category of modern manufacturing selection methods is based on MCDM analysis. This family of methods incorporate user experience

into decision-making, however, they are subjective and lack systematic guidelines on the elements and criteria that need to be considered in manufacturing process decision-making. Moreover, most relevant methods do not consider the key factors related to both the product and the process that significantly influence decision-making. As mentioned earlier, AM brings unique, often overlooked factors to process selection, underscoring the need for a more comprehensive approach.

6. **Sustainability and manufacturing**: The manufacturing sector has a substantial impact on sustainability, making it crucial to focus on more sustainable manufacturing practices. The design phase plays a critical role in determining the entire product lifecycle impact. Thus, deciding on a relatively more sustainable manufacturing process in the pre-conceptual design phase and applying guidelines such as DfX can significantly improve the sustainability impact. There is currently a need for comprehensive, user-friendly guidelines and tools to assist designers in this process, considering three dimensions of sustainability.

AM, as a disruptive technology, is closely tied to advanced digitalisation and so far its application has been limited to niche market segments. Still, there remains limited knowledge and experience on how to fully leverage AM in other industrial sectors. In this section based on literature and state of the art review, it was argued that bringing the needs and opportunities with AM systematically upfront in the design process, while better leveraging the available information and data, opens up new venues for exploring potential advantages offered by AM.

Chapter 4

Summary of the Papers

The outcomes of the research conducted to address the research questions are summarized in this chapter. The results of this effort are published in five appended papers. In this Chapter, first, the summary of each paper is provided followed by outlining the main findings and contribution to the thesis. To understand the correlation between the papers, research questions and different methodology steps please see Figure 2.4).

4.1 Paper A: The Role of Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing

4.1.1 Summary

The purpose of this paper is to highlight the critical role of digital infrastructure in DfAM as a key element in the industrial adoption of AM. For this purpose, a systematic literature review is conducted to investigate the existing DfAM methods and tools focusing specifically on digital infrastructure considerations. Further, results of a relevant industrial use case study are presented.

4.1.2 Findings

Several critical digital aspects that are overlooked or insufficiently addressed in existing DfAM methods have been identified, acting as barriers to the seamless adoption of AM. While DfAM primarily focus on design guidelines, few authors discuss the challenges, techniques, and opportunities related to digitalisation and its role in industrialisation and scale-up. In this paper, the importance of such considerations is highlighted. Below these aspects are briefly explained:

- Data format compatibility: Different DfAM methods and tools are often accessible through different software systems with varying data formats.

The lack of compatibility between these formats makes it challenging to integrate different tools and systems.

- Information management: Effective and efficient management of information throughout the entire value chain is critical. Information management in this context includes activities such as transferring, storing, tracing and retrieving information, which is currently given low attention in existing DfAM methods.
- Data analysis: The ability to interpret and analyse data is necessary for gaining insights into the AM process. Data cleaning is one of the examples, while essential, it is often time-consuming and prone to potential information loss. The need for cleaning or processing the data is largely overlooked in the available methods.
- Preservation of information: There is typically a potential for information loss when using a specific DfAM tool or method or when transferring information between them. This loss can stem from various factors, for instance converting CAD model to STL format or resolution limitations of scanners. It is critical to maintain data integrity throughout both the DfAM process and the entire value chain.
- Data and information reuse: The ability to trace and transfer data effectively is critical as it can be used to leverage knowledge generated by DfAM methods and tools. More effort is needed to benefit from generated data.

Considering these digital aspects affects both the effectiveness and efficiency of DfAM methods and thereby influences AM industrial adoption.

4.1.3 Contribution to the Thesis

This paper primarily contributes to the Research Clarification by identifying the missing digital aspects of DfAM that act as barriers to the seamless industrial adoption of AM. Therefore, this paper addresses RQ1.

4.2 Paper B: Information Flow Analysis Enabling the Introduction of Additive Manufacturing for Production Tools-Insights from an Industrial Case

4.2.1 Summary

In this paper impact of introducing AM to the information flow of the value chain is explored. The focus is on the effect of this change on the design phase. It explored how knowledge of the value chain and understanding of the changes can facilitate DfAM, ultimately supporting the appropriate industrial

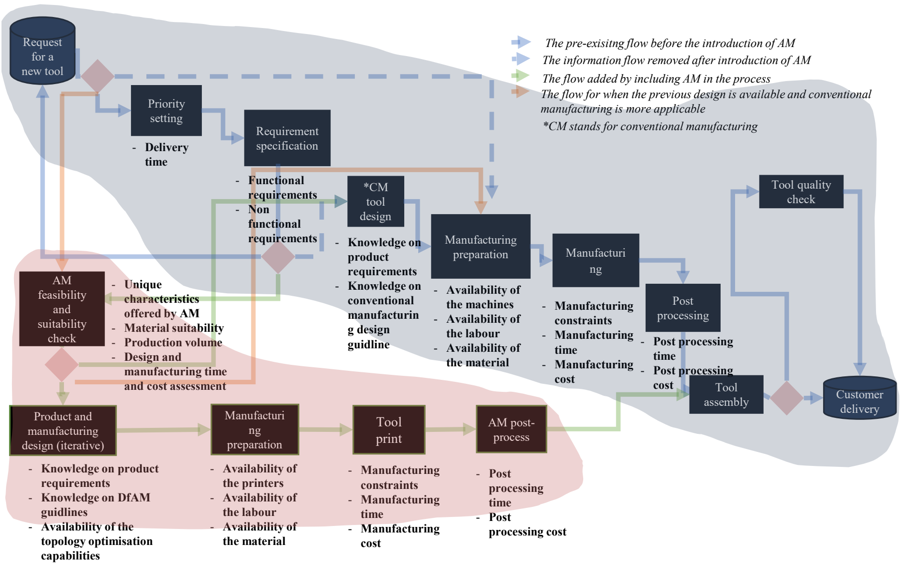

Figure 4.1: High-level view of value chain information flow with a summary of important criteria necessary for each activity step in the value chain, affecting design decisions.

adoption of AM. For this purpose, an industrial case study was conducted in collaboration with a large Swedish OEM.

4.2.2 Findings

In this paper it was argued that for smooth adoption of AM, apart from the knowledge on "how" to design for AM, it is equally important to know how the introduction of AM affects the existing value chain but also "when" to design for AM instead of other manufacturing processes. A key finding is the need to support designers to explore the suitability of AM when the decision on the manufacturing process is not straightforward. This decision should be made in the early design phase to guide the detailed design process. Further, it was highlighted that to make an informed decision on the suitable manufacturing process, information from various stages of the value chain needs to be collected and analysed (The result of the value chain information flow analysis in the case study is illustrated in Figure 4.1). This can be challenging due to high uncertainty in the early design phase as limited information about the product is available. In addition, currently, information of the value chain is significantly based on the engineers' experience and not formally captured.

4.2.3 Contribution to the Thesis

This paper revolves mainly around understanding the digitalisation aspects of the value chain that affect the design phase and integration of AM, therefore contributing primarily to the Research Clarification within the DRM framework. RQ1 is addressed by investigating elements that facilitate manufacturing process selection in the early design phase. Also, some of the key elements that need to be accounted for in manufacturing process decision-making are highlighted based on the case study, which indicates a minor contribution to RQ3.

4.3 Paper C: Sustainability Implications of Using Additive Manufacturing for Production Tool design

4.3.1 Summary

In this paper, the sustainability implications of using AM for redesign and remanufacturing products usually manufactured traditionally are explored. Further, the role of digitalisation in sustainable AM design and manufacturing is investigated. An industrial case study in collaboration with a large Swedish OEM was conducted to explore these themes.

4.3.2 Findings

In the studied use case, the role of design was highlighted as a key enabler for leveraging the sustainability benefits of AM. Three products were redesigned for AM revealing significant sustainability advantages in terms of product customisation, resource efficiency, functional enhancements and distributed manufacturing. These factors positively impact sustainability, however, the study uncovered several challenges and uncertainties. For instance, product longevity is unknown at the design stage; even if the new design requires less material consumption, a question arises regarding its durability. As another example, changes in both design and material may require revision of the quality assurance procedure, raising concerns about the economic and resource feasibility of such a change. Another critical challenge involves how to effectively incorporate all three dimensions of sustainability (environmental, economic and social) in the design phase. The paper emphasizes the need for such assessment in the early design phase, advocating for tools that are not only effective but also efficient and highly usable to ensure practicality in industrial practices.

In the paper, the role of digitalisation in sustainable design practices is also highlighted. As the digitalisation of manufacturing processes expands, companies can benefit from this opportunity to produce more sustainable products. For example, increased traceability throughout the product lifecycle can increase awareness of its sustainability implications, making digital threads or PLM systems particularly valuable. In addition, systematically collecting information about designed and manufactured products can leverage the application of various machine learning techniques, ultimately enhancing both the production process but also the product quality, leading to more sustainable production practices.

4.3.3 Contribution to the Thesis

This paper contributes to the understanding of sustainability implications required to consider when comparing various manufacturing processes. Thus, the paper primarily contributes to the RQ3 where a Descriptive Study is conducted to explore important sustainability factors for deciding on suitable manufacturing processes in the early design phase.

4.4 Paper D: A Decision Support Tool for Feasibility and Suitability Analysis of Additive Manufacturing in Pre-Conceptual Design Phase

4.4.1 Summary

In this paper key factors affecting manufacturing process decision-making in the early design phase are explained. Based on these identified factors, Manufacturing Process Decision Support (MPDS) is introduced which seeks to investigate and support the analysis of the feasibility and suitability of AM in advance of pre-conceptual design studies.

4.4.2 Findings

Key influencing factors affecting manufacturing process decisions in the early design phase are categories based on product and process. Product-related factors include criteria such as durability, flexibility of the structure and AM value enabling characteristics such as customisation and lightweight design. Process-related factors include for instance resource availability and resource constraints in terms of lead time and cost. These factors form the basis for the MPDS which is a MCDM based method that provides a guideline for manufacturing process decision-making in the early design phase. MPDS include two main steps, in the first step feasibility of AM is assessed whereas in the second step suitability of AM for manufacturing a product is explored. The key factors and high-level overview of the MPDS method are presented in Figure 4.2.

4.4.3 Contribution to the Thesis

Based on literature reviews and industrial observations, this paper presents key elements necessary for supporting manufacturing process decision-making in the pre-conceptual design phase. This prescriptive study mainly addresses RQ3.

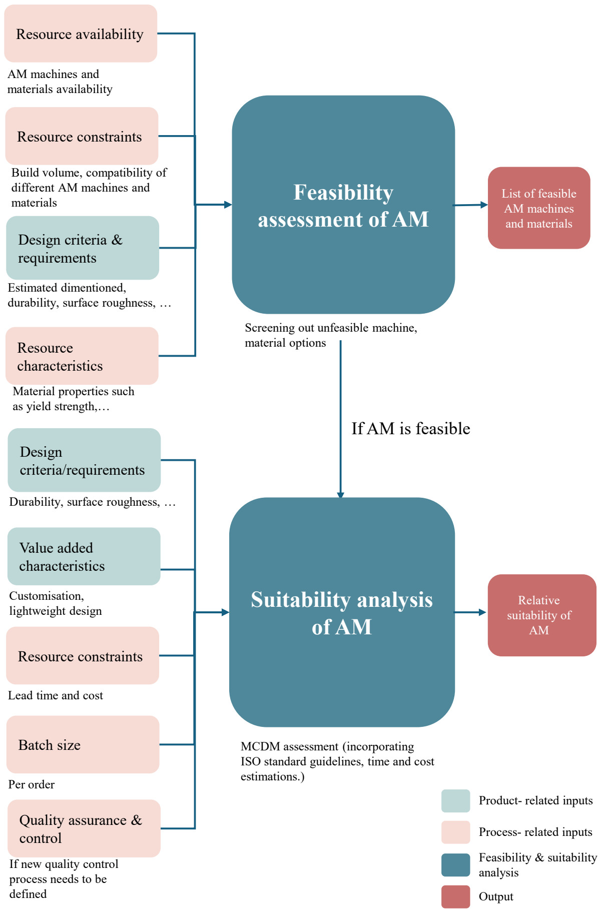

Figure 4.2: Overview of MPDS structure including the key factors as the inputs

Chapter 5

Discussion

In this section, each research question is discussed individually, based on the obtained results. .

5.1 Answer to the Research Question 1

What digitalisation aspects in the design phase are essential to consider for advancing the industrialisation of AM?

AM is closely tied to digitalisation, making digital aspects critical for the industrialisation of AM. The industrial case studies presented in Papers A and B revealed that the digital workflow in AM has **notable differences from CM** processes, impacting both the design process and the value chain. This has also been highlighted by Birtchnell and Urry, 2016 and Zimmermann et al., 2023. Design plays a pivotal role in the outcome, and incorporating data and information from the entire value chain can significantly enhance the design process. As a simple example, the type of available printers and their specifications directly influence design decisions. Given the differences between AM and CM process models, it is crucial to **systematically capture information** from both, which can help refine design practices. Digital thread solutions such as PLM systems can be used for this purpose.

Application of such systems can facilitate the **storage, transfer, traceability and retrieval of data and information** throughout the process chain, thereby enhancing the design processes. This can be especially useful for capturing information regarding quality assurance procedures. As the application of AM might necessitate **new quality requirements and test procedures**, capturing the relevant information can be of use. It provides designers with insights into how quality requirements influence design decisions, enabling informed adjustments to meet specific standards and optimise the design accordingly. Borgue et al., 2019 emphasized this need and introduced a method to integrate qualification requirements into the DfAM process.

Additionally, systematic information storage enables **the reuse of information** to optimise the product and process by using for instance AI techniques. As an example, ML can help optimise design parameters based on past manufacturing outcomes. However, it is important to ensure that the implementation of such solutions does not overcomplicate the process. A concern raised by designers in the case company participating in the DIDAM project was that the application of systems such as PLM could reduce process agility and efficiency which needs to be carefully considered.

When considering data storage and management in design for AM, it is critical to **prevent the loss of valuable information**. A vast amount of data is generated during the whole process and the challenge lies in determining **which data to capture and how to analyze** while ensuring no critical information is disregarded or lost. With the help of a systematic literature review, it was observed that current Design for AM guidelines often neglect this matter. Loss of information can also occur when using different software in the process. For instance when transferring from CAD to STL format some metadata and design features will be lost. Furthermore, **data format compatibility** is also one of the important elements to consider as different software may not support the same formats which can affect the process negatively.

Loss of knowledge is also a critical concern. Much of the design-related knowledge is tacit and not formally documented. As the value chain usually follows a relatively complex flow, much of this knowledge can be lost throughout the process. Further, it makes it challenging to understand how this knowledge can be applied or adapted for design for AM. To address this, solutions such as PLM have the potential to serve as data repositories, and also **manage important information** for learning and training purposes.

In cases where the comparison between AM and CM for design and manufacturing a part is difficult, it is recommended to develop a decision support system in the early design phase. This approach helps identify the appropriate manufacturing process and apply the relevant DfM guidelines. This can facilitate a shift in mindset from the CM way of thinking to also include AM design thinking. This can also highlight the unique potentials of AM that may otherwise be overlooked.

In summary, digitalisation aspects are crucial for the successful industrial adoption of AM which comes with significant challenges and risks. Many companies struggle to anticipate these risks, leading to potential implementation failure or costly refinements. Therefore, careful consideration of digital workflows, data management and integration strategies is critical for overcoming these barriers.

5.2 Answer to the Research Question 2

What are the existing methods and tools, along with their capabilities and limitations, that can assist in determining the suitability of AM during the pre-conceptual design phase?

To answer this question, the discussion is divided into two themes: design methods and tools, and manufacturing process selection methods.

1. **AM Design Methods and Tools:**

   Current DfAM guidelines primarily focus on optimizing designs to be suitable for the AM process by providing guidelines and recommendations for instance corner radius or overhang angle. These guidelines heavily focus on "shape", prioritizing geometric adjustments over fundamental design intent and product "function" (as also highlighted by Douglas C. Eddy and Steudel, 2019). Designers must first ensure that AM is a suitable manufacturing process before starting with detailed geometry assessments. This is also emphasized in the well-known DfAM book by Diegel et al., 2019. Unfortunately, current DfAM methods often overlook this critical stage, despite industrial observations confirming the need for such guidelines. The type of the manufacturing process affects the application of the relevant DfM guidelines.

   Furthermore, existing DfAM practices often give low consideration to the digitalisation aspect (as also highlighted by Wiberg, 2019). These methods largely ignore for instance, how to systematically store, trace and retrieve data and information. This oversight negatively affects the efforts for assessing manufacturing process suitability, as information on previously designed and manufactured products is not easily accessible, limiting the use of ML techniques for informed decision-making. In general, information regarding the product lifecycle, if formally captured, can effectively guide designers in the development of future products. Currently, much of this information remains tacit or poorly documented. As an example, in the case company, the design department has limited access to the information regarding the product once it is handed over to be manufactured.

2. **Manufacturing Process Selection Methods:**

   The existing manufacturing process selection methods can be divided into two categories: traditional methods and more recent methods that include AM as a competitive manufacturing process to CM methods.

   2.1 Traditional Methods
   Traditional methods such as the ones proposed by Lovatt and Shercliff, 1998 and Swift and Booker, 2003 provide guidelines on selecting suitable manufacturing processes for a given task mostly follow this

sequence: 1) Identify objectives (e.g., product hardness, strength and ductility requirements); 2) Screen unfeasible material and machine alternatives; 3) Proceed with detailed design; 4) Select the most suitable manufacturing alternative based on the product geometry. These methods delay the manufacturing decision until the final stages, allowing the detailed geometry to determine the process. This is a smart strategy because it avoids imposing design constraints early in the process, which can be challenging to modify later due to the design paradox (Ullman, 2009). However, this limits the advantages of DfM guidelines. Moreover, these methods are relatively outdated, often failing to consider AM as a viable alternative for producing final products.

2.2 More Recent Methods including AM:
More recent efforts have been made to assess the suitability of AM, though the number of publications remains significantly lower than those on DfAM. These methods can be divided into two types:

2.2.1 Geometry-based Methods
These methods share similarities with some current DfAM methods mentioned previously as the main focus is on product geometry. Typically, these methods analyze the CAD model to either assess its suitability for AM, offering recommendations for design adjustments if required or recommend a suitable manufacturing process for the given geometry. However, similar to the traditional methods, they overly rely on geometry, thus limiting the potential benefits of DfAM guidelines.

2.2.2 MCDM-based Methods
In contrast, in MCDM methods emphasize product functionality and criteria, comparing different manufacturing processes based on these factors. Therefore, possibilities to benefit from DfM guidelines are not limited in this case. However, these methods are user-dependent as the outcomes may differ depending on the individual utilizing the method. Further, they often lack systematic guidelines on the elements or criteria to consider in decision-making. Additionally, many of the available methods do not fully consider the critical factors related to both the product and process in manufacturing process decision-making.

An analysis of existing manufacturing process selection methods in the early design phase reveals a clear need for further development. Most methods overlook critical product and process factors that significantly influence decision-making for suitability analysis of AM in the early design phase. As AM introduces unique and often overlooked considerations, it is crucial to develop more comprehensive methods that address these specific factors to better support early manufacturing process decisions.

5.3 Answer to the Research Question 3

How can the feasibility and suitability analysis of AM be facilitated during the pre-conceptual design phase?

Based on the literature review and industrial observation, a manufacturing decision support method or tool should meet four essential criteria:

1. **Effectiveness:**
   The method needs to systematically consider the following elements to be considered as effective:
   - It needs to be able to assess both AM feasibility and suitability for a given part.
   - It needs to compare AM with CM in terms of lead time and cost.
   - The entire value chain needs to be considered when making such decisions, such as the influence on product quality assessment.
   - It needs to focus on the main functionality of the product and other important criteria.
   - AM value enabling characteristics such as customisation and light-weight design need to be considered which also triggers ideas for later stages of the design.
   - Sustainability assessment needs to be considered.
2. **Efficiency:**
   Industry constantly focuses on minimizing resource consumption. Hence, both the time and cost associated with using the method need to be minimised, and the application of the method should also contribute to lower overall resource consumption.
3. **Usefulness:**
   Users should find it valuable in making rational decisions on suitable manufacturing processes particularly when the comparison is complex. Both novice and expert users should be able to benefit from the tool; the possibility of guided analysis but also quick assessment in time-constrained situations. Effective visualization, such as the application of charts and graphs, should be prioritized over raw and tabular data for easier interpretation. Further, the tool must facilitate information traceability, allowing users to access and analyze previously analyzed products.
4. **Usability:**
   Any method or tool developed for this purpose needs to be user-friendly and intuitive, ensuring ease of use.

To address these criteria, the MPDS method was developed. MPDS assists in comparing AM with CM during the early design phase. The method comprises two key modules: AM feasibility analysis module and manufacturing process suitability analysis module which assist a comparative analysis between AM and CM for a given part. To ensure the effectiveness of the analysis, the method incorporates critical factors mentioned above both in terms of product design and process such as product criteria, value-enabling characteristics and time and cost assessments. Sustainability analysis was intentionally excluded, necessitating further research and collaboration with sustainability experts.

To ensure the usability of the method, a prototype software was designed with a user-friendly interface, incorporating visual tools such as charts to present results effectively. As one important limitation of the common AM design tools is the lack of a suitable information management system, critical information and data are systematically stored in the software back end to enable both traceability but also reusability to assist future manufacturing process assessments. MPDS inputs include information regarding the product, material, process, and user input, with the output (if AM feasible) being the relative suitability of AM compared for the case under investigation.

The benefits and novelty of the proposed support are as follows:

- MPDS has a dual character; both systematically guiding the users throughout the decision-making process and also recommending a suitable manufacturing process. Very few methods exist addressing manufacturing process selection in the early design phase. Among the ones that exist, one of the major limitations of the current manufacturing process selection methods applicable in the early design phase is the lack of suitable guidelines on how to systematically consider critical elements for decision-making in this case.

- The proposed support incorporates information from various stages of the value chain, including quality assessment which is not typically addressed in the current available methods. In MCDM, AM can be replaced by any other manufacturing technologies, adding to the versatility of the approach.

- MPDS helps systematically capture tacit knowledge, thereby enhancing decision-making for future designs. This also enables data traceability, addressing a common gap in current DfAM methods that often overlook the importance of digital considerations.

The Challenges are as follows:

- While MPDS provides a guided assessment and seeks to gather information from various stages of the value chain, two primary challenges complicate this process: 1) Since the assessment takes place in the early design phase, limited product information is available and uncertainty is high, making a thorough analysis difficult. For example, manufacturing time and cost need to be estimated, but accurate values are not yet obtainable. 2) Although useful information from different parts of the system or previously manufactured components could improve decision-making, the lack of a centralized information system often makes such data inaccessible or, if available, time-consuming to retrieve, thus reducing the overall efficiency of the method.

- To have better results, not only information regarding various steps of the value chain should be systematically captured, but also critical information from the product lifecycle needs to be collected. Achieving this level of integration is challenging, given the complexities and current lack of fully traceable product information.

- The method relies on MCDM analysis to reduce subjectivity in the decision-making process. However, user input still significantly influences the results. Incorporating an ML-based approach within the method could help provide recommendations to the user based on previously designed and manufactured products, making the process less subjective. In this context, the role of centralized digital solutions becomes even more important.

- Sustainability assessment is critical in comparing different manufacturing processes. AM is well-known to benefit sustainability as material consumption can be significantly reduced. However, sustainability assessment especially in the early design phase with limited information is complicated especially if all three elements of environmental, economic and social aspects are considered. Despite the critical importance, this assessment is intentionally excluded from the current version of the tool as more in-depth research and collaboration with sustainability experts are required.

5.4 Answer to the Research Question 4

What role does a prototype tool play in supporting the decision on suitability analysis of AM?

To advance the decision support for feasibility and suitability analysis of AM a prototype tool plays a critical role, serving as a tangible means to collect structured and valuable feedback from specialists and users. In this research, a prototype tool was designed to apply MPDS in practice. Apart from validation purposes, it helps to engage users to collect actionable feedback and insights leading to iterative improvements.

In fact, the MPDS method and tool were developed concurrently. First, the method was implemented in an Excel sheet, facilitating discussion with design engineers, through rounds of demonstrators and interviews, the tool gradually developed in the form of a software tool (for detail check Section 2.4). For example, designers requested charts and graphs for better readability over raw data, which were integrated into the next development round. Overall, the prototype facilitated a deeper understanding of the gaps and needs in real-world decision-making scenarios, highlighting key areas for improvement.

This process makes the method to be more aligned with the practical needs, increasing its robustness and applicability in an industrial setting. Ultimately, the prototype tool can be used to validate the method in terms of criteria such as effectiveness, efficiency, usability and usefulness. An initial validation study has begun but is not included in the current thesis.

Chapter 6

Conclusions and Future Work

In this chapter, the conclusion of the research is presented (Section 6.1), and the contributions to knowledge and practice are discussed (Sections 6.2 and 6.3), and recommendations for further research are presented in Section 6.4.

6.1 Conclusions

In this research, a critical but underexplored influence of digitalisation in design for AM is addressed. Digitalization plays a fundamental role in AM and requires significant attention when implementing these technologies, as it involves risks and challenges that must be managed. Ignoring these risks can lead to implementation failures or costly adjustments. Thus, careful consideration of digitalisation aspects including information and digital flow, data management and integration strategies is essential.

Moreover, the research tackles an important yet often overlooked question in design studies: "when" to design for AM instead of other manufacturing processes, rather than solely focusing on "how" to design for AM. Despite its potential, industrial adoption of AM is hampered by a lack of clear guidelines on this issue. In some cases, the feasibility and suitability of AM is clear, but cases in "grey zone" lack a suitable guideline that takes into account factors regarding both the design of the product and the ecosystem around it.

Available methods, both in literature and industry, analyze the product geometry. This approach might seem efficient as the product CAD model is imported and AM feasibility and suitability are estimated. However, this approach is not sufficient, as to fully leverage a manufacturing process, products need to be designed specifically for that process. Thus, a more effective approach needs stepping back to assess the product functionality and criteria assisting selection of the appropriate manufacturing process. This, however, is particularly challenging as information in the early design phase is limited and uncertainty is high.

Few studies focus on manufacturing process comparison analysis in the early design phase. Those that do often rely on MCDM methods, but they frequently lack a systematic guideline on which factors to consider during the assessment or may not fully address the key factors related to both the product and the process. Thus, the objective of this thesis is to emphasize the importance and complexity of such comparison analysis, identify the critical factors affecting such decision and finally propose a method to fill this gap.

Manufacturing Process Decision Support (MPDS) is proposed as a method and tool that facilitates the feasibility and suitability of AM for new product development initiatives. The method includes influencing factors regarding the product such as criteria, relevant value enabling AM characteristics and process including batch size and resource availability and constraints. It enables a systematic capture of information, thereby improving decision-making process transparency and traceability. However, challenges remain, including the need to capture, store, organise, manage and make use of available information and data that can be used to train decision support methods, e.g. by using AI techniques such as ML. Further, the incorporation of sustainability assessment as a critical assessment needs to be further investigated. These venues for further research are explained in more detail in Section 6.4.

6.2 Contributions to Science

The question of "how" to design for AM has received substantial attention so far. However, there is a knowledge gap in determining "when" to design for AM in assessing its suitability for specific part manufacturing before starting the design process. Specifically, there is limited understanding of how to leverage available information and data to better evaluate the suitability of AM. This gap is supported by evidence in both the literature and the empirical studies conducted and reported in this thesis. The contribution of this thesis is thus to clarify this gap and indicate what data and information need to be accounted for in advance of conceptual design studies.

6.3 Contributions to Practice

In the short term, this research contributes to raising awareness of the factors influencing the suitability assessment of AM in practical situations. In the medium term, it provides the industry with structured guidance through methods and tools that quantitatively support the assessment and evaluation of AM suitability. Over the long term, this work aspires to lower the barriers to the "appropriate" adoption of AM, fostering more informed, data-driven decision-making that integrates AM seamlessly into the design and manufacturing process.

6.4 Future Work

Future research should focus on improving the proposed method and tool based on validation studies and exploring its integration into the industrial sector. Further, key recommended areas for further investigations are elaborated below.

1. While MPDS provides a structured assessment by collecting information and data across the value chain, effectively capturing, storing, and utilizing this information remains challenging. Ensuring seamless integration for data capture, traceability and retrieval across the value chain and product lifecycle highlights a critical need for further research.

2. Further research is needed to explore the use of AI-powered solutions in this field to assess their impact on process effectiveness and efficiency. For example, ML models could predict suitable manufacturing processes based on past products or support the MCDM analysis by recommending values for the key factors. Additionally, natural language processing techniques could extract product requirements directly from order documents, or customized generative models could assist designers in identifying key product criteria and assigning importance weights to different factors. However, the quality of these outcomes will largely depend on the availability and quality of the underlying data, emphasizing the need for robust, high-quality data sources to support reliable AI-driven insights.

3. Sustainability is one of the most important elements in deciding the suitability of AM. However, assessing sustainability in the pre-conceptual design phase is challenging as limited information regarding the product or the value chain is available. A structured analysis is needed to consider various dimensions of sustainability in the decision-making process while considering the entire product lifecycle. This can be challenging as this type of analysis can potentially be resource-intensive, while the industry continuously seeks more efficient processes. There is a need to develop methods that are both more efficient and still effective in sustainability evaluation in the early design phase.

4. Finally, more research is needed to integrate decision-making principles into AM suitability analysis. This integration can provide additional insights and improve the decision-making process.

In summary, there are clear avenues for further research in this field, especially as the complexity of the manufacturing sector grows, where such decision support will be increasingly valuable. With technologies such as AM emerging today and the possibility of innovations in the future, continued effort is essential to ensure effective and adaptable solutions are developed to support future advancements.

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