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Facilitating the Integration of Additive Manufacturing in the Manufacturing Industry

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FACILITATING THE INTEGRATION OF ADDITIVE MANUFACTURING IN THE MANUFACTURING INDUSTRY

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To
Mom & Dad

Abstract

Additive manufacturing (AM), commonly known as 3D printing, is revolutionising the manufacturing industry by boosting business profits and enhancing their competitive edge. However, simply adopting and implementing AM technology is not enough. Manufacturing companies must integrate AM into their existing capabilities with which is a complex challenge. Therefore, the purpose of this thesis is to explore the integration of AM into the manufacturing industry by looking into what manufacturing companies find challenging and propose solutions to overcome the challenges. The research was conducted in collaboration with a global heavy vehicle manufacturer located in Sweden. The overall research methodology adopted a longitudinal multiple case study. So far, three studies emerged, namely the Strategy and Tactics study, the Gearbox study, and the Learn from Others study. Several participants were engaged in the whole or parts of the longitudinal multiple case study including managers and engineers from different departments. The findings were analysed thematically, and several tactics were used for enhancing validity and reliability. The findings from this research suggested four AM integration challenges, namely ambiguous ownership, cognitive fixation, situational awareness, and manufacturing fixation. To overcome these challenges, four operational capabilities were suggested, namely AM use cases, AM creativity, AM collaboration, and AM operational practices. These findings were formulated into short-term and long-term essential actions, sorted throughout the AM integration process, and presented in a facilitation framework. Manufacturing companies need to be aware that AM integration is more complex in industrial settings and should seek support from other manufacturing companies and AM actors when necessary. The next steps is to evaluate and test the facilitation framework and map AM integration challenges and operational capabilities of critical heavy vehicle AM use cases.

Sammanfattning

Additiv tillverkning (AT) är även allmänt känd som 3D-utskrift och revolutionerar tillverkningsindustrin genom att öka företagsvinster och förbättrar deras konkurrenskraft. Det räcker dock inte med att adoptera och implementera AT-teknik. Tillverkningsföretag måste integrera AT med deras befintliga förmågor, vilket är en komplex utmaning. Därför är syftet med denna avhandling att utforska integrationen av AT i tillverkningsindustrin. Detta genom att undersöka vad som är utmanande för tillverkningsföretag och föreslå lösningar för att övervinna utmaningarna. Forskningen har genomförts i samarbete med en global tillverkare av tunga fordon i Sverige. Den övergripande forskningsmetodiken antog en longitudinell multipel fallstudie. Hittills har tre studier antagits, nämligen Strategi- och Taktikstudien, Växellåda-studien och Lära sig av Andra studien. Flera deltagare inklusive chefer och ingenjörer från olika avdelningar var engagerade i hela eller delar av den longitudinella multipel fallstudien. Fynden från forskningen analyserades tematiskt och flera taktiker användes för att förbättra validitet och pålitlighet. Resultaten föreslog fyra AT-integreringsutmaningar, nämligen tvetydigt ägande, kognitiv fixering, situationsmedvetenhet och tillverkningsfixering. För att övervinna dessa utmaningar föreslogs fyra operativa förmågor, nämligen AT-användningsfall, AT-kreativitet, AT-samarbete och AT-operativa praxis. Dessa resultat formulerades till kortsiktiga och långsiktiga väsentliga åtgärder som sorterades genom hela AT-integrationsprocessen och presenterades i ett underlättande ramverk. Tillverkningsföretag måste vara medvetna om att AT-integration är mer komplex i industriella miljöer och bör söka stöd från andra tillverkningsföretag och AT-aktörer vid behov. Nästa steg är att utvärdera och testa det underlättande ramverket och kartlägga AT-integreringsutmaningar och operativa förmågor för kritiska AT-användningsfall för tunga fordon.

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I tried to make this acknowledgment short but failed. Even though the writing of this thesis marks the halfway point of my doctoral studies, I am truly blessed for all my experiences so far. Thereby, my final thanks go to God for guiding me and giving me hope through these endeavours.

Some final words for you that are reading this in the future, remember to "*work hard, study well, and eat and sleep plenty*".

Best wishes
Christopher Gustafsson

List of Papers

This thesis is based on the following appended papers, which are referred to in the text by their Roman numerals. The authors' contribution is presented after each appended paper.

I. Gustafsson, C., Sannö, A., Bruch, J. & Chirumalla, K. (2022). Exploring challenges in the integration of additive manufacturing. In: Kim, D.Y., von Cieminski, G. & Romero, D. (eds), *Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action (APMS 2022)*. September 25-29, Gyeongju, South Korea, pp. 370-379. https://doi.org/10.1007/978-3-031-16407-1_44

Contribution(s): All authors contributed to the study's conception and design. Material preparation was performed by all authors. Data collection was performed by Christopher Gustafsson. Initial data analysis was performed by Christopher Gustafsson. and additional data analysis was performed by all authors. The first draft of the manuscript was written by Christopher Gustafsson and all authors commented on previous versions of the manuscript. All authors commented on additional versions of the manuscript and the final manuscript during the peer review process. All authors read and approved the final manuscript. The full paper underwent a peer-review process from (usually) conference participating authors and was evaluated based on its industrial relevance and scientific quality.

II. Gustafsson, C., Sannö, A., Chirumalla, K. & Bruch, J. (2023). Integration of additive manufacturing in an industrial setting: the impact on operational capabilities. In: Alfnes, E., Romsdal, A., Strandhagen, J.O., von Cieminski, G. & Romero, D. (eds), *Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures (APMS 2023)*. September 17-21, Trondheim, Norway, pp. 590-604. https://doi.org/10.1007/978-3-031-43666-6_40

Contribution(s): All authors contributed to the study's conception and design. Material preparation was performed by all authors. Data collection was performed by Christopher Gustafsson. Initial data analysis was performed by Christopher Gustafsson and additional data analysis was performed by all authors. The first draft of the manuscript was written by Christopher Gustafsson and all authors commented on previous versions of the manuscript. All authors commented on additional versions of the manuscript and the final manuscript during the peer review process. All authors read and approved the final manuscript. The full paper underwent a peer-review process from (usually) conference participating authors and was evaluated based on its industrial relevance and scientific quality.

III. Gustafsson, C., Sannö, A., Chirumalla, K. & Bruch, J. (forthcoming). Additive manufacturing integration: an operational capability perspective. *Journal of Manufacturing Technology Management*. The first version was sent in February 2024. Recently submitted the second version in June 2024 and is under review.

Contribution(s): All authors contributed to the study's conception and design. Material preparation was performed by all authors. Data collection was performed by Christopher Gustafsson. Initial data analysis was performed by Christopher Gustafsson and additional data analysis was performed by all authors. The first draft of the manuscript was written by Christopher Gustafsson and all authors commented on previous versions of the manuscript. All authors read and approved the manuscript before submission. The same procedure was performed before the second submission to revise the Reviewer's comments. The full paper is undergoing a double-blind peer-review process and will be evaluated based on its industrial relevance and scientific quality.

IV. Gustafsson, C. (2024). Exploring the integration of additive manufacturing: lessons learned and success factors of use cases. In: Klahn, C., Meboldt, M. & Ferchow, J. (eds), *International Conference on Additive Manufacturing in Products and Applications: Industrializing Additive Manufacturing (AMPA 2023)*. September 12-14, Lucerne, Switzerland, pp. 423-439. https://doi.org/10.1007/978-3-031-42983-5_28

Contribution(s): Christopher Gustafsson contributed to the study's conception and design, material preparation, data collection, data analysis, writing the manuscript, and revising the manuscript. The abstract and the full paper underwent a double-blind peer-review process. The abstract was evaluated based on its industrial relevance by an industrial committee and the full paper was evaluated based on its scientific quality by a scientific committee.

Additional papers that emerged before or during the doctoral studies but are not included in this thesis are presented below.

A. Gustafsson, C., Chirumalla, K. & Johansson, G. (2018). Application of lean methods and tools in servitization: a literature review. In: Bitran, I., Conn, S., Huizingh, E., Kokshagina, O., Torkkeli, M. & Tynnhammar, M. (eds), *Proceedings of the XXIX ISPIM Innovation Conference: Innovation, The Name of the Game (ISPIM 2018)*. June 17-20, Stockholm, Sweden, 1-17.

B. Johnsson, M., Gustafsson, C. & Johansson, P.E. (2022). Disrupting the research process through artificial intelligence: towards a research agenda. In: Tanev, S. & Blackbright, H. (eds), *Artificial Intelligence and Innovation Management*, pp. 161-183. World Scientific. https://doi.org/10.1142/9781800611337_0009

Contents

Part I
The journey

1 Introduction

This chapter introduces the importance of additive manufacturing for the manufacturing industry. This is followed by the problems of integrating additive manufacturing into the manufacturing industry. Thereafter, the purpose and research questions are proposed. The chapter ends with the outline of the thesis.

1.1 Background

In 1951, Otto John Munz developed one of the first 3D printing patents of the photo-glyph recording and was considered the origin of the stereolithography technique (Diegel et al., 2020). Later in the early 1980s, the world was introduced to the first 3D-printed cup using a commercially available stereolithography system (Kanishka & Acherjee, 2023). This was achieved by Chuck Hull who became the inventor of the stereolithography apparatus. A few years later, this event paved way for the development and invention of selective laser sintering by Carl Deckard in 1992 and of fused deposition modelling by Scott Crump in 1993. In the last decades, 3D printing has now been standardised as additive manufacturing (AM) and was theorised[1] (or predicted) to disrupt and revolutionise the manufacturing industry (Kanishka & Acherjee, 2023; Steenhuis & Pretorius, 2017; Holmström et al., 2016).

AM has many uses ranging from rapid prototyping to high-volume production of complex final products (Stentoft et al., 2021; Ford et al., 2016; Gao et al., 2015). Furthermore, AM has been highlighted as one of many key enabling technologies for the manufacturing industry in Europe to improve sustainability, improve agility, improve first-time-right manufacturing, and ensure capabilities become widely diffused (Deliyanakis et al., 2023; European Commission, Directorate-General for Research and Innovation, 2018; Ford & Despeisse, 2016). Previous research has presented additional benefits with AM such as part consolidation, mass customisation, design freedom, lightweight parts, on-demand production, rapid prototyping, and waste reduction, among others (Gibson et al., 2021; Diegel et al., 2020; Holmström et al., 2010).

[1] Read more about the hype surrounding AM in the articles by Davies (2023), AMFG (2022), Peels (2022), and Simpson (2022).

Over the years, manufacturing companies have explored ways to adopt and implement the benefits. Adopting and implementing the broad variety of benefits have been prioritised differently by different industry sectors. Both the automotive sector and the aerospace sector prioritised complexity-for-free (design freedom), and the medical sector found customisation as the most important benefit, to name a few examples (Niaki et al., 2019). However, adopting and implementing AM technology is not enough as it does not ensure that AM becomes an integral (i.e., necessary and important) part of the existing capabilities, for example operational capabilities, at a manufacturing company.

> "For a successful integration of AM, it is necessary not only to know about the characteristics and benefits of AM itself. Gaining knowledge about the whole product development and production process from new product concepts to the production itself is crucial." (Reiher et al., 2017, p.44)

This means that AM integration is necessary and important with existing capabilities at a manufacturing company. Previous research in the AM literature mentioned that manufacturing companies have sought ways to enhance business profits and sustain competitive advantage (Niaki et al., 2022; Sonar et al., 2020; Niaki & Nonino, 2017a) by integrating new capabilities in existing product development (Handfield et al., 2022; Turkcan et al., 2022) and production (Singh et al., 2023; Haug et al., 2023). Integrating new capabilities could enhance existing products and production systems, for instance, rendering certain process steps in product development and production obsolete (Holmström et al., 2017; Kothman & Faber, 2016). Additional benefits of integrating new capabilities include, inducing new processes and operating routines (Roscoe et al., 2019), incrementally or radically improving company performance (Oduro et al., 2023), and driving changes to existing business models and supply chains (Friedrich et al., 2022b, 2022c; Öberg & Shams, 2019).

However, previous research has mainly focused on technical aspects of AM integration (see for example, Lynch et al., 2020; Renjith et al., 2020; Madden & Deshpande, 2015; Hedrick & Urbanic, 2013) leaving an opportunity to research AM integration more holistically. Manufacturing companies still find AM integration challenging despite the efforts of previous research to provide various potential solutions to overcome the challenges (see for example, De Lima et al., 2023; Gao et al., 2022; Rohde et al., 2019; Tosello et al., 2019).

1.2 Problem Formulation

Manufacturing companies find AM integration challenging due to its complexity (Gao et al., 2022, 2015; Yi et al., 2019; Bessant, 1985). This is related to managers and other decision-makers having difficulty in allocating resources for initiating AM investigations that lead to a business case (Chaudhuri et al., 2019). Once an AM investigation had been initiated, the workforce had difficulties in adapting and transitioning to the new capabilities whereas AM either complements or replaces traditional manufacturing (Roscoe et al., 2023; Rylands et al., 2016). Such a scenario induces an overall hesitation and reluctance due to the traditional attitude of the workforce which has been embedded in traditional manufacturing, often carrying many years of experience (Dwivedi et al., 2017; Flores Ituarte et al., 2016). These issues can be traced back to an overall lack of knowledge and understanding of the new capabilities such as design for AM, AM process chain, and AM materials (Fontana et al., 2019; Martinsuo & Luomaranta, 2018). However, these issues only scratch the surface of AM integration challenges.

To summarise, it is not enough to merely adopt and implement AM technology. Manufacturing companies should prioritise AM integration making the new capabilities a necessary and important part of existing capabilities. Previous research has reported a call to action to support manufacturing companies to take significant steps forward towards seamless AM integration (Basso et al., 2022; Yi et al., 2019; Ford et al., 2016). Thereby, this research emerged to identify what manufacturing companies find challenging with AM integration and provide support in overcoming such challenges.

1.3 Purpose and Research Questions

The purpose of this thesis is to explore the integration of AM into the manufacturing industry. Based on this background, the following research questions (RQ) are proposed.

- RQ1: What are the AM integration challenges in the manufacturing industry?
- RQ2: How can the manufacturing industry be supported to overcome the AM integration challenges?

1.4 Thesis Outline

This thesis comprises two parts. **Part I** serves as an introduction to **Part II** with the following structure. **Chapter 1** introduces the research and why it is important. **Chapter 2** presents the frame of reference including theoretical concepts and related studies. **Chapter 3** mentions the performed research methodology. **Chapter 4** summarises insights from the appended papers. **Chapter 5** discusses the findings and synthesises answers to the research questions. Lastly, **Chapter 6** concludes the key takeaways of this research. **Part II** contains the main part of the thesis which includes the appended papers.

2 Frame of Reference

This chapter presents the frame of reference including the important and relevant theoretical concepts and related studies.

2.1 Additive Manufacturing

AM includes several technologies allowing physical parts to be made from digital 3D models by building the part layer-by-layer until finished. In this thesis, the following definition is used.

> AM is referred to as the manufacturing "*process of joining materials to make parts from 3D model data, usually layer upon layer*" compared to traditional manufacturing such as machining, moulding, forming, and joining (ISO/ASTM 52900, 2021).

Integrating AM technology into different manufacturing industry sectors are easier said than done. However, before describing what makes AM integration challenging, it is essential to first define AM integration, beginning with a description of technology integration.

2.1.1 Integration of Additive Manufacturing into the Manufacturing Industry

Technology integration influences several departments (i.e., functional organisations) of a manufacturing company both within and across their borders (Gustavsson & Säfsten, 2017; Säfsten et al., 2014). In the interface between departments working with design and manufacturing, Vandevelde et al. (2002, p.6) referred technology integration to "*interaction processes involving information exchange on the one hand and collaboration or cooperation on the other*." Shaw et al. (2018, p.212) mentioned that technology integration goes "*beyond adoption and predicts future use"*, in which they further explain that *"developers can use these predictions to produce satisfying and beneficial products for the user*." Based on this background, in this thesis, AM integration is defined as follows.

AM integration is referred to as going beyond implementation and adoption making new capabilities an integral part of existing capabilities as well as predicts future necessary and important capabilities for a manufacturing company.

The AM integration process is complex (see for example Rylands et al., 2016) and is usually performed in simplified three-stage processes (see for example Luomaranta & Martinsuo, 2022; Chaudhuri et al., 2019; Deradjat & Minshall, 2017). In this thesis, a simplified integration process (Voss, 1988) consisting of three stages, namely pre-integration, integration, and post-integration, was used. Throughout the process, Voss (1988) proposed different factors that influence the success or failure of integration.

- *Pre-integration* refers to the overview and securing of capabilities for the success or failure of AM integration (Deradjat & Minshall, 2017). Factors include technical planning, strategic links, acquisition of skills, and top management support (Voss, 1988).
- *Integration* refers to ensuring the consistent and successful realisation of a working order with AM (Deradjat & Minshall, 2017). Factors include links with suppliers, workforce participation, champion, project management, implementation by cross-functional teams, and start-up management (Voss, 1988).
- *Post-integration* refers to applying continuous improvements of business- and technical-related activities with AM (Deradjat & Minshall, 2017). Factors include organisational change, managing the learning process, appropriate operational control, high-performance orientation, and changing the accounting system (Voss, 1988).

2.1.2 Factors Affecting Additive Manufacturing Integration

AM integration could be viewed on a broader and more holistic basis with the support of various factors presented and packaged in different frameworks. Mellor et al. (2014) proposed an AM integration framework to address the lack of socio-technical studies and the need for guiding AM project managers. The factors of the AM integration framework (Mellor et al., 2014) include external forces, AM strategy, AM supply chain, AM technology, system of operations, and organisational change.

Additionally, in the AM literature, different theories have been used to understand technology integration (Ukobitz, 2021). Among them, the technology-organisation-environment framework (Baker, 2012; Tornatzky et al., 1990) is an organisational theory that explores the factors of a company's acceptance of an innovation (such as advanced manufacturing technology) using the technology, organisation, and environment dimensions. Choudhary et al. (2021) used the technology-organisation-environment framework to analyse the barriers in the supply chain of the medical sector. Yeh and Chen (2018) extended the technology-organisation-environment framework with the addition of the cost factor to identify critical success factors of AM integration in the Taiwanese manufacturing industry. Umar (2021) utilised the technology-organisation-environment-cost framework to systematically review and identify key factors of AM integration in the construction industry. Tsai and Yeh (2019) extended the technology-organisation-environment-cost framework with the addition of the virtual community factor to empirically understand the decision rules of AM integration in the Taiwanese manufacturing industry. On the other hand, Priyadashini et al. (2022) used the factors of value and risk instead of cost in the framework to explore and prioritise the challenges of AM integration to achieve circular economy goals.

2.1.3 Challenges in Additive Manufacturing Integration

AM technology is not the only response or solution to every opportunity or problem in the manufacturing industry (Liu et al., 2023; Martinsuo & Luomaranta, 2018; Niaki & Nonino, 2017a; Mellor et al., 2014). Certain trade-offs and changes compared to traditional manufacturing should be considered such as required AM expertise, available capabilities, presence or absence of AM actors, various costs, and technology uncertainties, among others (Priyadarshini et al., 2022; Yi et al., 2019; Yeh & Chen, 2018; Steenhuis & Pretorius, 2017).

Next, I have summarised literature of AM integration challenges. Chekurov et al. (2021) reported that engineers in the machine-building industry expressed a lack of the necessary experience and knowledge about design for AM and AM materials. Yi et al. (2019) identified that the lack of knowledge of AM technologies was the most prominent challenge in identifying suitable AM applications. On the other hand, Flores Ituarte et al. (2016, p.240) mentioned that the involved company only uses AM for rapid prototyping and that decision-making related to certain products was supported by "*fake models*" produced by AM. Priyadarshini et al. (2022) identified that the lack of a company-wide strategy for AM made it difficult to align the workforce toward sustainability goals through digitalisation. Alsaadi (2021) identified that the workforce perceived learning about new technologies as too time-consuming. Dwivedi et al. (2017) found there were difficulties in introducing change in the traditional attitude of designers due to the prohibitive cost of AM integration. Martinsuo and Luomaranta (2018) identified the lack of available data from customers, referring to the lack of data entered into 3D models. Dwivedi et al. (2017) found that manufacturing companies had a lack of trust in AM service providers due to lacking after-sales services, spare parts control, low technical knowledge, and absence of communication. Flores Ituarte et al. (2016) revealed that conservative companies and the industry in general were still waiting for the big industry players to take the initiative with AM. Yi et al. (2019) found that many companies cannot exactly predict and define the relevant benefits of AM. Niaki and Nonino (2017a, p.69) identified the presence of "*hidden cost*" referring to the disposal cost of filters used in AM machines. Mellor et al. (2014) reported a lack of capital for investment in AM technology and research and development activities, thereby hindering an increase in capacity and the development of production applications. Priyadarshini et al. (2022) pointed out the potential legal issues with AM referring to the capability of illegal production of weapons, sharing of digital files, and piracy. Yi et al. (2019) found that when companies perceived unpredictable risk with AM, they would prefer to stay with traditional manufacturing. Martinsuo and Luomaranta (2018) identified that small- and medium-sized subcontractor companies expressed being afraid to invest in AM machines due to high investment costs and non-guaranteed payback.

2.1.4 Potential Solutions to Overcome the Challenges in Additive Manufacturing Integration

Even though I have presented a compilation of various AM integration challenges mentioned in previous research, some studies have provided examples of solutions to overcome them (see for example, Luomaranta & Martinsuo, 2022; Stentoft et al., 2021; Strong et al., 2018). These solutions are not a "one size fits all" for all challenges and consider company size, industry sector, make-or-buy scenario, selecting parts for AM, transforming use cases into business cases, and collaboration with AM actors, for example (Öberg & Shams, 2019; Reiher et al., 2017; Flores Ituarte et al., 2016; Knofius et al., 2016).

Next, literature of potential solutions to overcome the challenges in AM integration are summarised. Fontana et al. (2019) emphasised the need for understanding in design for AM and AM process chain depending on the AM application. Martinsuo and Luomaranta (2018) emphasised the need for AM actors to advance the maturity of AM technology and that digitalisation could support these advancements. Friedrich et al. (2022a) identified four decision profiles (pioneers, combiners, planners, and waverers) that demonstrated the spectrum of governance structures guiding make-or-buy decision-makers in industrial AM. Chaudhuri et al. (2019) identified that collaboration with AM service providers could support companies throughout the whole AM integration process. Rylands et al. (2016) found that AM can complement traditional value streams with limited business impact through changes in the value proposition. Stentoft et al. (2021) pointed out the opportunities and limitations of collaborating with a non-profit association referring to the signing of non-disclosure agreements hindering certain knowledge sharing. Rylands et al. (2016) identified that, if AM-based value streams co-exist with traditional manufacturing value streams rather than replacing them, this provided the company with market agility to respond or to anticipate change. Mellor et al. (2014) found that the location of manufacture remained centralised and that locating production according to demand could emerge from an established customer base. Klahn et al. (2020) identified several value-adding benefits that impacted many departments in a company. Deradjat and Minshall (2017) mentioned that a company adapted to the new capabilities as AM provided innovative technology and materials for dental applications. Rylands et al. (2016) revealed that a company added metal AM to the product offering to remain competitive. Roscoe et al. (2019) explained that moving from traditional learning through trial-and-error to ad hoc problem-solving and learning-by-failing increases the frequency of interactions between individuals. Deradjat and Minshall (2017) identified that certain AM machines were more suitable for mass customisation in the dental sector. Additionally, Deradjat and Minshall (2017) found a need for AM-based incentives for sceptic customers and suppliers referring to the free-of-charge offering of test objects taking years to recover from.

2.2 Operational Capability Theory

A manufacturing company has two kinds of capabilities, (1) operational capabilities (Wu et al., 2010), also known as ordinary capabilities[2] (Teece, 2019) or organisational capabilities[3] (Teece et al., 1997), and (2) dynamic capabilities[4]. Operational capabilities have been introduced as a way for manufacturing companies to adapt, innovate, and reshape their existing capabilities in response to changing environments (Teece, 2019; Wu et al., 2010; Teece et al., 1997).

2.2.1 Operational Capabilities in a Manufacturing Company

Operational capabilities originate from the field of strategic management and the resource-based view emphasising the role of a company's capabilities in creating and sustaining competitive advantage (Teece, 2019). Wu et al. (2010, p.726) refer to operational capability as "*firm-specific sets of skills, processes, and routines, developed within the operations management system, that are regularly used in solving its problems through configuring its operational resources.*" Additionally, operational capability also includes company-specific sets of facilities, equipment, administration, and coordination (Teece, 2019).

[2] Ordinary capability is not included in this thesis.
[3] Organisational capability is not included in this thesis.
[4] Dynamic capability is not included in this thesis.

Against this background, in this thesis, operational capability is defined as follows:

> Operational capability refers to company-specific sets of skills, processes, routines, facilities, equipment, administration, and coordination developed by the company and used for problem-solving or fulfilling needs through combining, joining, and mixing.

Operational capabilities are particularly interesting since they can explain a company's capabilities for different operational purposes (Teece, 2019; Wu et al., 2010). Thereby, operational capability includes:

- *Skill sets* refer to, for instance, specific abilities, competence, knowledge, and expertise that an individual possesses required to perform a particular task.
- *Facilities and equipment* refer to, for instance, physical and digital resources necessary for the operations of a company.
- *Processes and routines* refer to, for instance, systematic and repeated actions used to accomplish tasks or achieve goals.
- *Administration and coordination* refer to, for instance, management of resources and the coordination of efforts to achieve desired outcomes efficiently and effectively.

2.2.2 Development of Operational Capabilities

The operational capability literature mentions that there is "*no one-size-fits-all model*" for the development of operational capabilities (Wiengarten et al., 2023, p.56). There are two interesting approaches to develop operational capabilities. Teece (2019) suggests that operational capabilities can be developed (or augmented) through make, buy, and rent. Recently, Momeni et al. (2023) found that operational capabilities in the context of digital servitisation can be developed through acquiring, building, and learning mechanisms. Both approaches to developing operational capabilities suggest that the development mechanisms can be used alone or in combination.

Based on this background, the following development mechanisms have been used in this thesis:

- *Acquiring* refers to how companies develop operational capabilities from external actors (Momeni et al., 2023). For example, purchasing from external actors or hiring key people with the required know-how.

- *Building* refers to how companies develop the operational capabilities of internal departments, external actors, and customers (Momeni et al., 2023). For example, connecting people with certain know-how to another person or group of people over a longer-lasting period to extend their know-how base.

- *Learning* refers to how companies develop operational capabilities in-house (Momeni et al., 2023). For example, selecting and developing people through training and exposing them to new know-how.

The use of operational capability theory in the AM literature is limited. Roscoe et al. (2019) studied how individuals, processes, and structures interact forming the micro-foundations of operational capability in a digital manufacturing environment. Holmström et al. (2017) explored the design and integration of AM-based operational practices in manufacturing companies and guided them toward developing sustainable operations strategies. There are additional studies that have indirectly studied operational capability in AM contexts (see for example Friedrich et al., 2022a; Meyer et al., 2021; Ruffo et al., 2007).

3 Research Methodology

This chapter describes the performed research methodology including the research approach, research design, research process, data collection, data analysis, research quality, and ethical considerations.

3.1 Research Approach

The research was conducted in collaboration with a global heavy vehicle manufacturing company[5] located in Sweden. I was accepted as an industrially financed doctoral student in an industrial graduate school called the Automation Region Research Academy (ARRAY++)[6]. Adopting different roles, such as being an observer, analyst, and consultant, for example (Karlsson, 2016), throughout the research process was difficult to manage. This was mitigated by adopting a reflective view (i.e., careful thinking) that provided me with (1) a careful interpretation of the results and (2) a careful interpretation of the interpretation (Alvesson & Sköldberg, 2017; Schön, 2013). For instance, careful interpretation of the results was performed by checking for similarities and differences of the results with the literature and initiating informal meetings with industry professionals.

After initial discussions with engineers and managers at the global heavy vehicle manufacturer and initial scanning of the AM literature, early formulations of the purpose and the research questions were formulated. However, this formulation was done in several iterations using problematisation (Alvesson & Sandberg, 2011) throughout the research process until the finalisation of this thesis. To summarise, the global heavy vehicle manufacturer wanted to explore the opportunities and limitations of AM technology, a relatively new phenomenon for the global heavy vehicle manufacturer. The phenomenon could be (1) studied in an industrial setting, (2) meaningful and relevant generated theory could be gained through actual practice, and (3) studied where variables are relatively still unknown, and the phenomenon not completely understood. Additionally, previous research (see for example Niaki & Nonino, 2017b) in the AM literature has called for more case study research. Based on

[5] The global heavy vehicle manufacturing company also referred to as the global heavy vehicle manufacturer have different descriptions in the appended papers.

[6] Read more about ARRAY++ here: https://sites.mdu.se/array

this call for action, case study research was deemed suitable (Yin, 2018; Karlsson, 2016; Eisenhardt, 1989).

3.2 Research Design

With the selection of the case study research, the next step was to specify the case study design, case study type, case study selection, and unit of analysis.

3.2.1 Case Study Design

The research was initially planned by taking inspiration from the multiple case study guidelines (Yin, 2018; Karlsson, 2016). Additional inspiration was taken from longitudinal case study guidelines (Pettigrew et al., 2001; Pettigrew, 1990, 1985) and process study guidelines (Langley et al., 2013; Langley & Truax, 1994).

The multiple case study format was useful to explore AM integration holistically throughout the company across several departments compared to limited single-case studies (Yin, 2018; Karlsson, 2016). Holistically meant that I could study several aspects of the AM integration phenomenon throughout several studies. Additional inspiration from the longitudinal case study guidelines and the process study guidelines helped me capture *change* over a period that included AM technology and its industrial context. I was able to gain an understanding of the current status by identifying the details of specific technical and managerial changes throughout the organisation. Then, I was able to shift to the holistic, multifaceted, and dynamic analysis of *changing* over a period (Avital 2000; Pettigrew, 1990). I could capture what was and what should or could be changing of specific technical and managerial changes throughout the organisation.

Thereby, the selected case study design for this research was a longitudinal multiple case study of AM integration in collaboration with a global heavy vehicle manufacturing company. This choice provided additional insights into previous research who used different case study designs such as multiple-case studies (e.g., Chekurov et al., 2021; Chaudhuri et al., 2019; Martinsuo & Luomaranta, 2018), single case studies (e.g., Flores Ituarte et al., 2018; Mellor et al., 2014), and literature studies with empirical validation (e.g., Yeh & Chen, 2018; Dwivedi et al., 2017).

3.2.2 Real-Time and Retrospective Case Studies

Since this research was planned to expand over the course of five years, I had the opportunity to perform studies both in real-time and retrospectively. The retroactive studies allowed me to capture insights into historical events regarding change over time and the process of changing to AM integration. However, disadvantages with retroactive studies relate to (1) the difficulty in determining cause and effect, (2) participants may have difficulties in recalling essential details of important events or being too biased when recalling memories, and (3) reports produced by companies might not examine all events and might only present important events for their own benefit (Karlsson, 2016; Voss et al., 2002; Leonard-Barton, 1990). To overcome the disadvantages of retrospective studies, real-time studies were performed. The real-time studies allowed me to capture insights into current events regarding change over a longer period and the process of changing with AM integration. Disadvantages of real-time studies include (1) having long elapsed time, thus being difficult to manage, (2) potential researcher influence or bias in ongoing important events, and (3) reports produced by companies are made available at the end of an event (Karlsson, 2016; Voss et al., 2002; Leonard-Barton, 1990).

However, early on, I became aware that other manufacturing companies were also on or had been a part of a similar AM journey as the global heavy vehicle manufacturer. Thereby, I included insights from other companies' AM journeys to potentially "avoid reinventing the wheel".

3.2.3 Case Study Selection and Unit of Analysis

I chose to collaborate with the global heavy vehicle manufacturer, in addition that they financed the greater part of my doctoral studies, and also based on opportunistic sampling (Patton, 2002). The following criteria were used since the global heavy vehicle manufacturer (1) develop and manufacture complex products such as heavy vehicles and most of their parts and components, (2) utilise AM for different operational purposes throughout the company, and (3) had previous experience working with AM technology.

In collaboration with the global heavy vehicle manufacturer, I initiated three studies, namely, (1) the Strategy and Tactics study, (2) the Gearbox study, and (3) the Learn from Others study. The *Strategy and Tactics study* was selected to gain broader insights (e.g., strategic and tactical aspects of AM integration) from the managers working at four departments, namely Technology, Operations, Purchasing, and Sales. The *Gearbox study* was selected to gain in-depth insights from engineers working with product development and production of parts and components in gearboxes. Additionally, to explore the potential impact of AM integration on the product development and production of parts and components in gearboxes. The *Learn from Others study* was selected to gain broader insights (e.g., lessons learned and success factors) from other manufacturing companies in various industry sectors and AM actors such as service providers, machine providers, universities, and research institutes. Based on this background, the unit of analysis for the three studies focused on AM integration in the context of AM integration-related studies. A summary of the research design is presented in **Table I**.

Table I *Overview of the Research Design*

Case Study	Study Type	Unit of Analysis	RQ	Paper
Strategy and Tactics	Real-time	AM integration	1, 2	I, III
Gearbox	Real-time	AM integration	1, 2	II, III
Learn from Others	Retroactive	AM integration	2	IV

RQ refers to the research question. Descriptions of the sample: Internal refers to samples originating from the global heavy vehicle manufacturer. External refers to samples originating from other sources outside the global heavy vehicle manufacturer.

3.3 Research Process

In the research, I would freely move between theory and empirical data back and forth with several starting points and exits throughout the research process (Van de Ven, 2007).

The longitudinal multiple case study started in 2019 and was officially kicked off following the start of my doctoral studies on the 1st of April 2021. Shortly thereafter, I summarised and presented my research proposal. The Strategy and Tactics study started in September 2019 and the Gearbox study started in September 2021. The initial results from the Strategy and Tactics study were published in September 2022 (see Paper I). Thereafter, initial results from the Gearbox study were published in September 2023 (see Paper II). Then, the combined results from both the Strategy and Tactics study and the Gearbox study were synthesised and sent to a journal for a 1st review in February 2024 and 2nd review in June 2024 (see Paper III). In November 2022, the Learn from Others study started, and initial results were published in September 2023 (see Paper IV). An overview of the research process is presented in **Figure 1**.

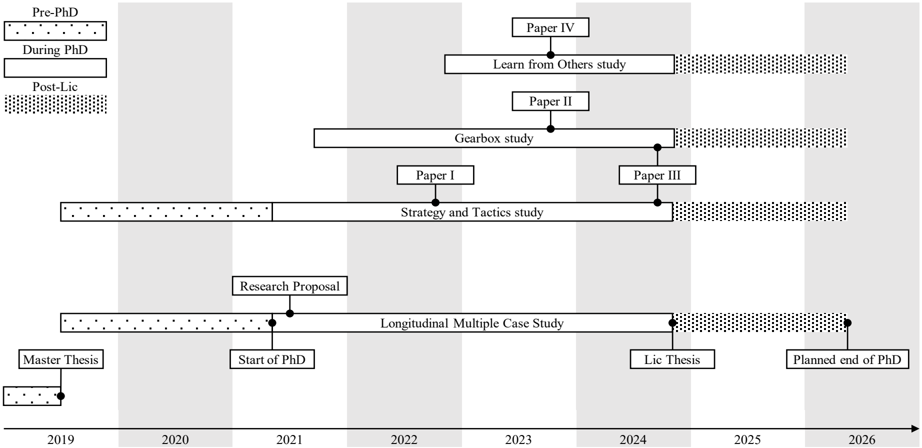

Figure 1 *Overview of the Research Process*

3.4 Data Collection

In the longitudinal multiple case study, three different studies were initiated to collect data from and provide answers to the research questions.

3.4.1 The Strategy and Tactics Study

The Strategy and Tactics study collected broader insights from managers focusing on the strategic and tactical aspects of AM integration.

Qualitative data was collected to provide rich descriptions of AM integration (Creswell, 2014). Before starting my doctoral studies, a focus group[7] (Coghlan & Brydon-Miller, 2014) was set up at the global heavy vehicle manufacturer with managers in various roles from four departments such as Technology (i.e., research and development, and product development), Operations (i.e., production), Purchasing, and Sales (see **Table II**). The included departments were selected due to their relevancy to technology integration (Andreasen & Hein, 1987). Throughout the research process, the participants in the focus group changed over time due to the changing of roles within the company, or leaving the company for other opportunities, for instance.

The focus group sessions were selected to enable the participation of all participants in the same (digital) space and provide engaging discussions about AM integration. The questions used and the overall focus group design is presented in **Appendix A**. A total of three focus group meetings (Session 1

[7] At the global heavy vehicle manufacturer, the focus group was also a reference group or steering committee as part of my doctoral studies. This group provided me with additional support and a channel for me to report back various insights and findings throughout the doctoral studies.

in May 2021, Session 2 in March 2022, and Session 3 in August 2023) were conducted as part of the data collection and were between 30 minutes to 1 hour long. If a participant was unable to participate in a focus group session, a separate interview was scheduled. In cases where the participant did not want to participate in an interview, an email was sent instead. The interviews were semi-structured with a similar design and the same questions as in the focus group sessions. Semi-structured interviews were selected to enable the participants to freely answer the questions and let the overall discussion flow while adding subsequent questions as guidance. All focus group sessions and interviews were held online through Teams and both audio and video were recorded. I collected additional data from informal meetings with company employees and external AM experts, observations (for example, tours in some of the company's factories, online and offline seminars, and workshops), company files (documents, reports, and presentations, etc.), and extensive field notes from informal meetings, project meetings, observations, and company files.

Table II *Overview of the Participants in the Strategy and Tactics study*

Designation[8]	Role[9]	Department	Work Experience[10]	Geographic Location[11]	AM Knowledge
Participant A	Head of aftermarket parts	Sales	3	Sweden	Beginner
Participant B$^{\alpha}$	Project manager of parts	Purchasing	7	Sweden	Beginner
Participant C$^{\gamma}$	Head of manufacturing technology development and governance	Operations	5	Sweden	Beginner
Participant D$^{\alpha}$	Head of research engineers	Technology	6	Germany	Beginner
Participant E$^{\delta}$	Head of research strategy	Technology	5	Sweden	Beginner
Participant F$^{\delta}$	Head of advanced manufacturing engineering and research	Operations	4	Sweden	Beginner
Participant G	Head of strategic procurement	Purchasing	11	United States	Beginner
Participant H	Head of virtual product development	Technology	19	Sweden	Beginner
Participant I	Head of purchasing controls	Purchasing	13	Sweden	Beginner
Participant J$^{\beta}$	Head of research strategy and innovation	Technology	5	Sweden	Beginner
Participant K$^{\varepsilon}$	Head of business development	Purchasing	1	Sweden	Beginner
Participant L$^{\varepsilon}$	Head or research strategy	Technology	1	Sweden	Beginner
Participant M$^{\varepsilon}$	Head of advanced manufacturing engineering and research	Operations	1	Brazil	Beginner
Participant N$^{\varepsilon}$	Head of sustainable materials	Technology	1	Sweden	Beginner

α: Changed roles in 2024, β: Changed roles in 2022, γ: Left company in 2024, δ: Left company in 2023, ε: Started this role in 2023

[8] Additional participants (Participants K-M) were included (seen in Paper III but not in Paper I). Participant N was not part of the data collection process of the study (i.e., not included in Paper I & III). However, Participant N made significant contributions to other areas in the study. Participant B switched roles in 2024 compared to what was reported in Paper I & III.

[9] Participant B and Participant D switched roles within the company in 2024. Participant C left the company in 2024. Participant E and Participant F left the company in 2023. Participant J switched roles within the company in 2022. Participants K-N started their roles in 2023.

[10] Work experience is shown for the current role only. The compilation of work experience reported in Paper III shows differences in years compared to Paper I depending on whether the participants were still in their current roles, switched roles, or left the company.

[11] Participant M moved to Sweden in 2024.

3.4.2 The Gearbox Study

The Gearbox study collected in-depth insights from engineers focusing on the product development and production aspects of AM integration based on parts and components in gearboxes.

Qualitative data was collected to provide rich descriptions of AM integration (Creswell, 2014). Quantitative data was collected to provide numerical explanations to certain descriptions and variables of AM integration (Creswell, 2014). This study emerged as a call to action by previous research (see for example Niaki & Nonino, 2017b) to dive deeper into AM use cases. The gearbox was selected based on the following criteria[12] (1) it was a product that was currently or has been designed and produced by the global heavy vehicle manufacturer, (2) the product is complex due to a significant number of parts and components, multi-functionality, and multi-material, (3) the product is highly driven by customers' requirements, (4) previous research showed interesting results to the design and production of other gearboxes, and (5) the product is a critical part of heavy vehicles. Then, I selected machine elements such as gears, shafts, and gear stages or gear trains for further data collection, analysis, and synthesis. A total of 12 design concepts of gears, shafts, and gear stages or gear trains were developed. In other words, I created four design concepts for each of the selected machine elements. I followed the action design research guidelines (Sein et al., 2011) using Creo 9 CAD software with AM-related applications when designing the concepts. The concepts highlighted the following designs of a gear, shaft, and gear stage or gear train: (1) the original design, (2) using gyroid lattice structures in the design, (3) using topology optimisation in the design, and (4) combining gyroid lattice structure and topology optimisation in the design. The purpose of the design concepts was to use them as part of the interviews, to showcase the potential of AM integration into the design of such machine elements and the whole gearbox, and to gain insights into further developing the design concepts.

In addition to collecting data for the creation of the design concepts, I also conducted semi-structured interviews with five of the participants (Participants O-S in **Table III**). I collected qualitative data from the interviews about the product development and production of gears, shafts, gear stages or gear trains, the interface between product development and production, as well as insights on AM integration. The questions used for the interviews are presented in **Appendix B**. All the interviews averaged 1 hour in length, were held online through Teams, and both audio and video were recorded. I conducted the interviews in January and February of 2023.

I collected additional data from informal meetings with company employees and external AM experts, observations (for example, tours in some of the company's factories, online and offline seminars, and workshops), company

[12] Additional criteria were added to strengthen the selection of the gearbox compared to what was presented in Paper II.

files (documents, reports, and presentations, etc.), and extensive field notes from informal meetings, project meetings, observations, and company files.

Table III *Overview of the Participants in the Gearbox study*

Designation[13]	**Role (Area of Expertise)**[14]	**Department**	**Work Experience**[15]	**Geographic Location**	**AM Knowledge**[16]
Participant O	Product development engineer (gears and shafts)	Technology	28	Sweden	Beginner
Participant P	Design engineer (Gears)	Technology	16	Sweden	Intermediate
Participant Q	Manufacturing engineer (Gears)	Operations	25	Sweden	Beginner
Participant R	Product development engineer (Shafts)	Technology	35	Sweden	Beginner
Participant S	Production engineer (Shafts)	Operations	23	Sweden	Beginner
Participant T	Research owner (Machine concept)	Technology	1	Sweden	Beginner

3.4.3 The Learn from Others Study

The Learn from Others study collected broader insights from other manufacturing companies and AM actors focusing on the lessons learned and success factors of AM integration.

This study emerged as a call to "avoid reinventing the wheel" and gain insights from other companies on AM integration. I collected both qualitative data and quantitative data from specific AM use cases. In contrast to the description of a case study, a use case is referred to as the "*…application of a technology for a specific operational purpose*" (Maghazei et al., 2022, p.568). Qualitative data provided rich descriptions of AM integration and quantitative data was extracted as a complementary explanation of AM integration (Creswell, 2014). The collected data from the use cases was secondary data that was already published online as customer stories by three AM actors, namely EOS, Materialise, and 3D Systems. I selected the AM actors based on intensity sampling (Patton, 2002) since they presented information-rich use cases that

[13] Participant T was not part of the data collection process of the study (i.e., not included in Paper II & III). However, Participant T made significant contributions to other areas of the study.
[14] I had to schedule a second interview to finish the interview guide with Participant S. Participant T switched roles in 2024.
[15] Work experience is shown for the current role only.
[16] Participant P mentioned that they have AM experience and knowledge from using AM machines or desktop 3D printers using polymer materials in their spare time.

manifest AM intensely but not extremely. The selection criteria included (1) the AM actor had a significant impact in the AM field in terms of research and development, (2) the AM actor had a clear connection and collaboration with the manufacturing industry, and (3) the AM actor had a relatively large portfolio of AM use cases with insights from a wide variety of sectors.

A total of 42 retrospective AM use cases (see **Table IV**) were selected. I selected the use cases based on opportunistic sampling (Patton, 2002) since they provided insights into AM integration in various contexts. The selection criteria included (1) the use cases having structured information mentioning one or several challenges, solutions, and results, and (2) the use cases having relevant information beneficial for manufacturing companies in the heavy vehicle sector. Data about the AM use cases was collected in November 2022.

Table IV *Overview of the selected AM Use Cases for the Learn from Others study*

Designation[17]	Use Case	Type	Sector	Country
Case 01	Flow measurement probes	Enhanced design	Aerospace	Germany
Case 02	Knuckle (axle-pivot)	Enhanced design	Academia	Germany
Case 03	Door handle cover	Custom products	Automotive	France
Case 04	Drill bit and rotary steerable system	Enhanced design	Energy	United States
Case 05	Heat exchanger	Enhanced design	Automotive	Australia
Case 06	Small burner	Enhanced design	Energy	Germany
Case 07	Rapid repair of burner tips	Process concentration	Energy	Sweden
Case 08	Tool insert and injection moulding component	Production tools	Production	Czechia
Case 09	Air cooling system	Enhanced design	Academia	Germany
Case 10	Oil cooling system	Enhanced design	Academia	Germany
Case 11	Spare parts management system	Improved delivery	Automotive	Germany
Case 12	Vacuum gripper	Enhanced design	Production	Canada
Case 13	Robotic hand	Enhanced design	Production	Germany
Case 14	Circuit carrier	Improved delivery	Production	Germany
Case 15	Bionic gripper	Enhanced design	Production	Germany
Case 16	Grip system	Enhanced design	Production	Austria
Case 17	Extraction gripper	Production tools	Production	Germany
Case 18	Software-based configurator	Incremental product launch	Production	Germany
Case 19	Fluorescent tube fixtures	Custom products	Transportation	Germany
Case 20	Physical scale model of solar car	Prototyping	Academia	Belgium
Case 21	Personalised car speaker grill	Custom products	Automotive	Belgium

[17] Reference for each of the selected AM use cases can be found in Paper IV since the same designation is used.

Table IV *(Continued)*

Designation[18]	Use Case	Type	Sector	Country
Case 22	Production fixtures	Production tools	Automotive	Belgium
Case 23	Shift gear	Enhanced design	Automotive	Germany
Case 24	Investment casting pattern	Production tools	Production	United States
Case 25	AM facility	Incremental product launch	Academia	Belgium
Case 26	Injector head	Enhanced design	Aerospace	Germany
Case 27	Injection mould	Enhanced design	Production	United States
Case 28	Investment casting pattern	Production tools	Production	United States
Case 29	Conformal cooling inserts	Production tools	Production	United States
Case 30	Investment casting pattern	Production tools	Production	United States
Case 31	Cooling system	Enhanced design	Production	The Netherlands
Case 32	Semiconductor original equipment manufacturers	Enhanced design	Production	The Netherlands
Case 33	Customised cars	Custom products	Automotive	United States
Case 34	AM for prototyping	Prototyping	Production	United States
Case 35	Accumulator	Enhanced design	Automotive	United Kingdom
Case 36	Automotive development	Incremental product launch	Automotive	Switzerland
Case 37	Quality control system	Improved delivery	Marine	Germany
Case 38	Autonomous underwater vehicle	Prototyping	Academia	United States
Case 39	Industrial fixtures	Improved delivery	Production	China
Case 40	Moulded elastomeric parts	Improved delivery	Automotive	United Kingdom
Case 41	Gearbox	Enhanced design	Automotive	New Zeeland
Case 42	Water pump housing	Enhanced design	Automotive	United States

[18] Reference for each of the selected AM use cases can be found in Paper IV since the same designation is used.

3.5 Data Analysis

All collected data from the studies was continuously analysed with a varied in-depth frequency throughout the longitudinal multiple case study. Before starting the initial data analysis in each of the studies, all collected data was manually transcribed[19] and compiled into Word documents. All the transcribed data was labelled and listed. Thereafter, I compiled all transcriptions into Excel documents for further analysis and synthesis.

In the Strategy and Tactics study and the Gearbox study, I had to consider a strategy for managing confidential data. Thereby, removing certain data[20] that did not provide significant relevance and substance in the analysis process. The selected strategy was the winnow approach (Guest et al., 2012) since it is a "*process focused in on some of the data and disregarding other parts of it*" (Creswell, 2014, p.245).

Since I would be collecting a lot of qualitative data from all the studies, the most suitable strategy would be to use thematic analysis. Themes (i.e., patterns in the data that are particularly interesting or important) of different abstraction levels were identified. The themes were used to interpret and make sense of the data. Inspiration[21] was taken from different thematic analysis methods (for example, Eisenhardt, 2021, 1989; Miles et al., 2019; Gioia et al., 2012) in a three-stage analysis process.

1. The compiled data was open-coded by using various colours and grouping text into first-order concepts.

2. Axial coding was used for grouping the first-order concepts into second-order themes.

3. A higher-level abstraction of the axial coding was used by comparing second-order themes to third-order dimensions[22].

[19] I have explored the software NVivo for qualitative data analysis, but I have yet to establish a good working routine with the software as I genuinely like the "old school" way better for some reason.

[20] An example of such data could be that the participant started answering the question but at some point, continued to talk about other irrelevant things.

[21] When looking back at the appended papers, "taking inspiration from" is a more suitable description of how we analysed collected data compared to what was written in the actual papers. For example, when looking into how Gioia et al. (2012) present their methodology by going from data structure to grounded theory, our results are not 100% solely based on Grounded Theory as such. We tried to see which of the data and how the data would fit into already existing theoretical frameworks, while simultaneously looking at the data that would not fit, thereby potentially highlighting new findings.

[22] We initially described third-order dimensions as aggregated dimensions based on Gioia et al. (2012), however, based on my collective understanding of the thematic analysis methods (see e.g., Eisenhardt, 2021, 1989; Miles et al., 2019; Gioia et al., 2012) the description is clarified in this thesis.

This three-stage analysis process helped me identify overlapping or emerging concepts that potentially contribute to new theoretical insights (Eisenhardt & Graebner, 2007; Eisenhardt, 1989). In all the studies, both the data collection and data analysis processes were performed with several iterations until reaching theoretical saturation[23] (Braun & Clarke, 2021; Low, 2019; Rowlands et al., 2016; Bowen, 2008). This meant that additional collected data or analysed data did not add any significant new insights to the research findings. Additionally, during the iteration process, I followed the guidelines of theorising (Swedberg, 2012) to (1) see, observe, and contemplate emerging theoretical concepts, themes, and dimensions in the data, and (2) name, conceptualise, explore analogies, metaphors, and types, develop tentative theories, and explain emerging theoretical concepts, themes, and dimensions in the data. Moreover, triangulation[24] (Flick, 2018) was used during the entire data analysis process to constantly compare findings from multiple sources. On the other hand, in the Learn from Others study, I performed a descriptive analysis to describe the findings based on a range of scores (Creswell, 2014). For instance, a percentage distribution of AM use case types, sectors, and country.

The three-stage analysis process and triangulation were used to make sense of the findings and provide answers for RQ1 (*What are the AM integration challenges in the manufacturing industry?*) and the first part of answers for RQ2 (*How can the manufacturing industry be supported to overcome the AM integration challenges?*). The AM integration framework (Mellor et al., 2014) was initially used to analyse the findings. Thereafter, the technology-organisation-environment-value-risk framework (Priyadarshini et al., 2022) was used to analyse the findings. This analysis was performed to gain a holistic understanding of AM integration extending beyond a company's acceptance of an innovation and the existing AM integration framework (Mellor et al., 2014). The second part of the answers for RQ2 took inspiration from the context-intervention-mechanism-outcome framework (Holmström et al., 2017; Denyer et al., 2008) in making sense of and formulating the findings. For instance, to overcome a challenge (outcome) in an integration stage (context), an operational capability (intervention) should be developed (mechanism) based on the selected strategy (context) by the responsible department (context).

[23] To determine when data collection and data analysis has reached theoretical saturation was (and still is) highly difficult to know. When it was time to report the results from a project (e.g., present and publish a conference paper), we decided that then, the findings were theoretically saturated enough.

[24] Triangulation was not explicitly mentioned in Paper II, but the analysis process matched the triangulation description which was clarified in this thesis.

3.6 Research Quality

To examine the sufficient quality of the case study research, it is suggested to test research quality concepts such as construct validity, internal validity, external validity, and reliability (Yin, 2018). A summary of the applied tactics for enhancing validity and reliability is presented in **Table V**.

Concerning *construct validity*. Triangulation was used in both the Gearbox study and the Learn from Others study but was not explicitly mentioned in Paper II and Paper IV. In the Learn from Others study, the findings were reported back to the global heavy vehicle manufacturer but were not explicitly mentioned in Paper IV. Moreover, there was only a single data collection method used but was mitigated by collecting data from multiple sources.

Regarding *internal validity*. Adopting the reflective view (i.e., careful thinking) in data collection and data analysis reduced the influence of other factors, for instance, when making wrong assumptions. This was mitigated by communicating the assumptions with colleagues, other researchers and industry professionals, and revisiting the literature, for instance.

Referring to *external validity*. Findings from the Strategy and Tactics study and the Gearbox study are heavily influenced by the heavy vehicle sector and should be critically reflected upon before being applied to other sectors. Findings from the Learn from Others study have so far been adapted to support the heavy vehicle sector.

Respecting *reliability*. Protocols were developed over time in the Strategy and Tactics study, the Gearbox study, and the Learn from Others study. In the Strategy and Tactics study and the Learn from Others study, pilot testing has yet to be performed, and only initial evaluation was done with the participants. This also included the Gearbox study and only initial evaluation of design concepts was done. The Learn from Others study has yet to include primary data, so an interview guide and audio and video recordings have not been used but were mitigated by a large amount of collected secondary data.

Table V *Applied Tactics for enhancing Validity and Reliability (Inspiration from Smith, 2018; Yin, 2018; Bruch, 2012; Olausson, 2009)*

Concept	Tactics	Study A	Study B	Study C
Construct validity	Key concepts from previous research	X	X	X
	Multiple data collection methods	X	X	N/A
	Review from stakeholders	X	X	(X)
	Triangulation	X	(X)	(X)
	Informal meetings	X	X	X
	Presentations at events	X	X	X
	Academic and industrial supervisors and mentors	X	X	X
Internal validity	Discussions with colleagues	X	X	X
	Associated literature	X	X	X
	Color-coding	X	X	X
	Pattern matching	X	X	X
	Triangulation	X	X	X
	Communication of assumptions	X	X	X
External validity	Transparency	X	X	X
	Replication logic	X	X	X
	Generalisability	X	X	X
	Transferability	X	X	X
Reliability	Extensive field notes	X	X	X
	Review of documents	X	X	X
	Systematic work procedures	X	X	X
	Observations	X	X	X
	Online meetings	X	X	X
	Offline meetings	X	X	X
	Interview guide	X	X	N/A
	Audio recordings	X	X	N/A
	Video recordings	X	X	N/A
	Protocols	(X)	(X)	(X)
	Evaluation	X	(X)	(X)
	Pilot testing	(X)	N/A	N/A
	Steering committee	X	X	(X)
	Academic and industrial supervisors and mentors	X	X	X
	Informal meetings	X	X	X

Description of the studies; Study A: Strategy and Tactics study, Study B: Gearbox study, and Study C: Learn from Others study. Description of the tactics; X: used tactics, (X): partially used tactics, and N/A: used tactics not available/applicable.

3.7 Ethical Considerations

In all the studies, it was important for me to consider intersubjectivity (Wheeldon, 2010; Morgan, 2007). This concerned the sharing of subjective experiences with different stakeholders within and across the different studies. The language I used in which the experiences were shared needed to be adapted depending on the intended or unintended recipient. For example, it was not beneficial to use academic terms with industry professionals who may or may not be familiar with those terms, thus potentially hindering the transferability of knowledge. I informed all involved participants before data was collected (for example from focus group sessions and interviews) and intended for research purposes (data analysis and reporting in publications, etc.). The participants were allowed to actively choose to participate or leave at any time during data collection. The data I collected was usually summarised before reporting back to the individual respondent or collective focus group.

Another important area I had to consider was the access to and use of confidential information such as information security, information classification, information lifecycle, and intellectual property. Regarding information security, I followed company guidelines for handling specific documents (reports, and presentations) and other files (CAD, CAE, CAM files, etc.). Then, for information classification, I classified specific information (metadata, for instance) before sharing, thus making sure the recipients had the necessary accessibility to specific information. Concerning the information lifecycle, I had an initial plan in the research proposal for the creation and collection of information from the data collection methods, use of data in data collection and data analysis methods, distribution (sharing and spreading) of information, maintenance of information (for example using the company's database for data storage), and disposal of information (regularly emptying the trashcan on the computer, and using specific paper shredders, for instance). Lastly, in intellectual property, I had to contain certain information and be careful when sharing information to consider different property rights such as trademarks, copyrights, and potential patents.

4 Summary of Appended Papers

This chapter summarises the appended papers that are published and papers that are in the review process, as well as the contributions of the appended papers to this thesis.

4.1 Paper I: Exploring Challenges in the Integration of Additive Manufacturing

This section provides a summary of Paper I and the main contributions to the thesis.

4.1.1 Summary of Paper I

The purpose of this paper was to identify the challenges in the integration of AM that management faces in large manufacturing companies. 20 AM integration challenges were identified and synthesised from a focus group of 10 participants working in four department and additional data collection. The results suggested the emergence of the added value dimension, thus extending the existing AM integration framework. Three (not essential but rather exemplified) actions to overcome an AM integration challenge in each integration stage were proposed. Lastly, future research should investigate solutions containing proper actions and capabilities to overcome AM integration challenges to facilitate AM integration step-by-step.

4.1.2 Contributions of Paper I to the Thesis

The main contributions of this paper are:

- The paper emerged from the Strategy and Tactics study.
- Identification of AM integration challenges that were sorted into the three stages of integration to provide answers to RQ1.
- Proposal of exemplified actions to overcome (a few) AM integration challenges to provide answers to RQ2.

4.2 Paper II: Integration of Additive Manufacturing in an Industrial Setting: The Impact on Operational Capabilities

This section provides a summary of Paper II and the main contributions to the thesis.

4.2.1 Summary of Paper II

The purpose of this paper was to explore changes in operational capabilities and their impact when integrating AM into a traditional manufacturing company. 57 operational capabilities were identified. Whereof, 27 operational capabilities were identified in the empirical findings from semi-structured interviews with engineers, action design research involving the use case of parts and components in a gearbox of heavy vehicles, and additional data collection. The remaining 30 operational capabilities were identified in the literature. The findings were categorised based on an existing operational capability framework, in which two new factors had emerged namely stakeholders and strategy. All the identified operational capabilities were compiled, and the findings suggested six priorities of operational capabilities that the global heavy vehicle manufacturer should consider as the next step in AM integration. Lastly, future research should investigate operational capabilities from other AM use cases, develop dynamic capabilities, and transform required operational capabilities and suggested priorities into guidelines and best practices for industry professionals such as engineers, managers, and other decision-makers at the global heavy vehicle manufacturer and other manufacturing companies.

4.2.2 Contributions of Paper II to the Thesis

The main contributions of this paper are:

- The paper emerged from the Gearbox study.
- Identification of operational capabilities based on findings from an industrial use case and literature to provide answers to RQ2.
- Suggested a set of priorities consisting of operational capabilities for AM integration and highlighting potential changes to existing operational capabilities to provide answers to RQ2.

4.3 Paper III: Additive Manufacturing Integration: An Operational Capability Perspective

This section provides a summary of Paper III and the main contributions to the thesis.

4.3.1 Summary of Paper III

The purpose of this paper was to explore AM integration in a global manufacturing company from an operational capability perspective. The findings presented in Paper I and Paper II of identified AM integration challenges were combined with additional findings from industry professionals in engineering roles and additional data collection. Initially, the data was categorised based on the technology-organisation-environment-value-risk framework. The analysis suggested the emergence of additional factors such as usage, tradition, and image, further extending the framework and the discourse about integration in the AM literature. The results suggested the emergence of four challenges and four operational capabilities in AM integration. The challenges and operational capabilities were sorted into the three stages of integration, which revealed the addition of the need stage before the pre-integration stage. Thereafter, which operational capabilities were required to overcome the challenges were mapped, thus proposing four essential actions. Lastly, future research should propose activities for each operational capability to realise the proposed essential actions throughout the AM integration process, investigate the transformation of the AM use case into a business case, and showcase how dynamic capabilities are developed from operational capabilities.

4.3.2 Contributions of Paper III to the Thesis

The main contributions of this paper are:

- The paper emerged from both the Strategy and Tactics study and the Gearbox study.
- Identification of AM integration challenges to provide answers to RQ1.
- Identification of operational capabilities to provide answers to RQ2.
- Identification of short-term and long-term essential actions to overcome the AM integration challenges with the operational capabilities to provide answers to RQ2.

4.4 Paper IV: Exploring the Integration of Additive Manufacturing: Lessons Learned and Success Factors of Use Cases

This section provides a summary of Paper IV and the main contributions to the thesis.

4.4.1 Summary of Paper IV

The purpose of this paper was to present propositions for facilitating the integration of AM for manufacturing companies in the heavy vehicle sectors based on identified success factors and lessons learned from use cases with different operational purposes. Six success factors emerged from analysing the AM use cases based on the technology-organisation-environment-cost framework and five lessons learned emerged from thematically analysing the data of the AM use cases. These findings were based on 42 retroactive AM use cases containing secondary data published online as customer stories by three world-renowned AM companies, namely EOS (19 use cases), Materialise (4 use cases), and 3D Systems (19 use cases). The success factors consisted of technology infrastructure, relative advantage, organisational readiness, competitive pressure, expectations of market trends, and trading partners. On the other hand, the lessons learned included additive thinking, AM management (named management aspects in the paper), practice makes perfect, AM acceptance, and AM experts. On this basis, the success factors and lessons learned were sorted into the three stages of integration. Thereafter, three propositions were presented, one proposition for each integration stage, to facilitate AM integration. Lastly, future research should investigate the emergence of additional success factors and lessons learned, the relationships between them, turning the success factors and lessons learned into guidelines and best practices, and investigate operational capabilities and dynamic capabilities.

4.4.2 Contributions of Paper IV to the Thesis

The main contributions of this paper are:

- The paper emerged from the Learn from Others study.
- Identification of success factors and lessons learned in AM integration based on a wide variety of AM use cases to provide answers to RQ2.
- Derived propositions of facilitating AM integration to provide answers to RQ2.

5 Discussion

This chapter discusses the findings from the appended papers with the extant frame of reference and synthesises answers to the suggested research questions. To recap the purpose of this thesis is to explore the integration of AM into the manufacturing industry.

5.1 Challenges in Additive Manufacturing Integration

Based on the purpose, and to recap RQ1 which states, "*What are the AM integration challenges in the manufacturing industry?*", this section provides answers to RQ1 and discusses the findings of the Strategy and Tactics and the Gearbox studies with the literature. To conclude, the findings revealed four categories of AM integration challenges, namely ambiguous ownership, cognitive fixation, situational awareness, and manufacturing fixation (see **Figure 2**).

Ambiguous ownership emerged because of the marginalisation of AM technology throughout the company and perceived inherent AM technology risks by the workforce (Paper III). The marginalisation of AM technology is connected to the challenges regarding organisational change, system of operations, and AM strategy (Paper I). On the other hand, the perceived inherent AM technology risks relate to the challenges regarding AM technology, AM supply chain, organisational change, and system of operations (Paper I). The findings suggested that the workforce throughout the company were waiting for one department to make a decision. Managers and engineers from the Operations and Purchasing departments expressed the need for someone at the Technology department to confirm certain AM activities or initiatives. For instance, to confirm that certain AM polymer materials were ok to use for certain spare parts and that certain AM parts could be used in daily production. The waiting issue can be seen at a company level rather than on a department level in the manufacturing industry (Flores Ituarte et al., 2016). On the other hand, managers from the Technology department expressed that each department should be responsible for using AM in their respective functions. The waiting issue then became an ownership issue. This was caused by the limited coordinated responsibility and difficulty in prioritising AM initiatives coupled with the limited awareness of technical risks in the workforce throughout the company. Consequently, this leads to the limited willingness to further invest in and use AM technology in traditional manufacturing (Martinsuo & Luomaranta, 2018).

Cognitive fixation resulted from the AM knowledge gap and a narrow perception of AM technology by the workforce (Paper III). The AM knowledge gap is linked to AM technology, organisational change, and system of operations (Paper I). On the flip side, a narrow perception of AM technology is associated with AM technology, organisational change, system of operations, and AM strategy (Paper I). For instance, it was mentioned that a 5kg weight reduction on a hydraulic manifold block mounted on a 5-ton heavy vehicle machine had low value. The suitability of AM for hydraulic manifold blocks could be questioned. Depending on whether the parts were designed for AM or simply adapted for AM and requested operational performance (Diegel et al., 2020). On the other hand, there were no requests in enhanced operational performances in addition to the weight reduction on the hydraulic manifold block. The exemplified knowledge gap and narrow perception are still an issue among industry professionals embedded in traditional manufacturing (Yi et al., 2019; Mellor et al., 2014). Meaning that the way of thinking and reasoning are limited to traditional manufacturing.

Situational awareness stemmed from the limited awareness of AM suppliers and the cognitive shift with AM technology in the workforce (Paper III). The limited awareness of AM suppliers is affiliated with the AM supply chain (Paper I). Conversely, the cognitive shift with AM technology is linked to organisational change (Paper I). When ordering the same part (e.g., cover) with the same material (e.g., nylon) from three or more AM suppliers, managers and engineers need to be aware that the part will look different, have different tolerances, and have different mechanical properties, etc. (Chekurov et al., 2021). Therefore, managers and engineers in the Purchasing department faced difficulties in identifying and selecting suitable AM actors for low-volume AM polymer spare parts production. Consequently, this leads to the workforce not knowing there are AM suppliers in the first place due to the lack of knowledge in AM. Previous research has not specifically mentioned the awareness issue of AM suppliers by manufacturing companies but rather highlighted the lack of additional post-processing capabilities (Chaudhuri et al., 2019) and the lack of trust in AM suppliers (Dwivedi et al., 2017).

Manufacturing fixation stemmed from the limited knowledge of the utilisation of AM technology and the limited understanding of value realisation with AM technology by the workforce (Paper III). The limited knowledge in the utilisation of AM technology is associated to the AM technology, AM supply chain, organisational change, system of operations, AM strategy, and external forces (Paper I). Then again, the limited understanding of value realisation with AM technology is connected to organisational change, system of operations, AM strategy, and added value (Paper I). For instance, the design engineers expressed having a limited view that specifically targeted traditional manufacturing aspects when exploring new design concepts of an incrementally or radically improved gearbox. The manufacturing aspects ranged from limited knowledge in design for AM, selecting and using suitable AM materials and AM processes to understanding what value (e.g., enhanced operational performance and other benefits) could be gained from using AM technology for the gearbox. Additionally, the findings suggested that if the workforce had seen a clear value with AM, then the global heavy vehicle manufacturer would have progressed more with AM. Today, AM technology still has unpredictable value and risk, thus implying that many manufacturing companies will continue to use traditional manufacturing (Yi et al., 2019).

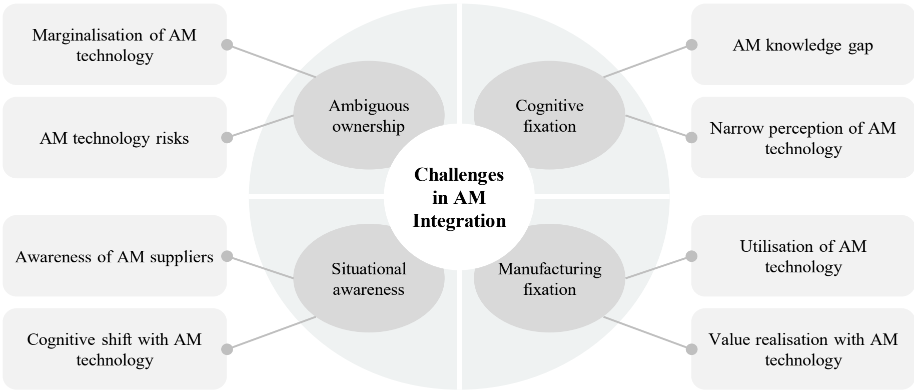

Figure 2 *Challenges in AM Integration*

5.2 Supporting the Manufacturing Industry to Overcome the Additive Manufacturing Integration Challenges

Based on the purpose, and to recap RQ2 which states, "*How can the manufacturing industry be supported to overcome the AM integration challenges?*", this section provides answers to RQ2 and discusses the findings of the Strategy and Tactics, the Gearbox, and the Learn from Others studies with the literature in two sub-sections.

5.2.1 Operational Capabilities in Additive Manufacturing Integration

The findings from the Strategy and Tactics and the Gearbox studies, revealed four categories of operational capabilities, namely AM use cases, AM creativity, AM collaboration, and AM operational practices (see **Figure 3**).

AM use cases emerged from the capitalisation of quick wins with AM technology and the recognition of critical AM applications by the workforce

(Paper III). The capitalisation of quick wins with AM technology is connected to strategy, skill set, processes, and routines (Paper II). On the other hand, the recognition of critical AM applications is related to skill set, strategy, facilities, and equipment (Paper II). Over the years, the global heavy vehicle manufacturer has been pursuing attainable and low-risk opportunities (i.e., low-hanging fruit) mainly for low-volume AM polymer spare parts, production tools, and rapid prototyping. Therefore, these applications of AM technology should be integrated into all factories at the global heavy vehicle manufacturer. However, to pursue other value-driven opportunities (e.g., enhanced design, custom products, process concentration, and incremental product launch) a certain understanding of both design for AM and the AM process chain is required (Fontana et al., 2019). Additionally, the findings suggested a need to demonstrate critical parts and applications relevant to the heavy vehicle sector.

AM creativity resulted from proficiency in AM design, AM production, and AM economics and the cultivation of AM thinking for the workforce (Paper III). The proficiency in AM design, AM production, and AM economics is associated with skill set, facilities, equipment, administration, and coordination (Paper II). In contrast, the cultivation of AM thinking is affiliated with skill set, processes, routines, facilities, and equipment (Paper II). The global heavy vehicle manufacturer must have trained designers in today's modern knowledge and tools, referring to AM technology, since previous knowledge in traditional manufacturing has started to become outdated. There is a need to learn about optimisation and simulation compared to the trial-and-error approach that was still being used by the workforce. Additionally, ad hoc problem-solving and learning-by-failing (Roscoe et al., 2019) coupled with sufficient re-engineering and redesigning parts for AM (Luomaranta & Martinsuo, 2022) should not only increase product development speed but also enhance operational performance. The findings suggested a need to extend existing traditional manufacturing creativity with AM creativity in the workforce.

AM collaboration stemmed from the involvement of people and teams with AM expertise and the support from key AM actors for the workforce (Paper III). The involvement of people and teams with AM expertise is attached to administration, coordination, stakeholders, facilities, equipment, processes, and routines (Paper II). Conversely, the support from key AM actors is related to skill set, stakeholders, and strategy (Paper II). It is important to hire individuals engaged in AM on a part-time or full-time basis and thereby gradually making AM an inherent capability for the workforce. However, having one or a few individuals engaged in AM in-house is not enough and collaboration with external AM actors is needed. Manufacturing companies are encouraged to collaborate with non-profit organisations (Stentoft et al., 2021) and centres of competence (Roscoe et al., 2019) to lower the AM integration threshold and enhance existing operational capabilities. However, the findings have not suggested what kind of collaboration is needed for the global heavy vehicle manufacturer.

AM operational practices stemmed from a new way of working with AM technology and value capture with AM technology by the workforce (Paper III). A new way of working with AM technology is affiliated with facilities, equipment, processes, and routines (Paper II). However, value capture with AM technology is linked to processes, routines, administration, coordination, and strategy (Paper II). AM should be utilised where it aligns with logical and strategic imperatives and where AM technology is placed closer to end-users. For instance, there was a new way of working in a production line by employing AM for rapid prototyping to assess the manufacturability of a new shaft before proceeding with serial production. Shifting from the traditional trial-and-error to ad hoc problem-solving and learning-by-failing might take time and should be embraced by the workforce (Roscoe et al., 2019). It is recommended to start with small-scale experiments and research without a definitive and immediate direct business case benefit and then scale up AM deliveries in selected niche products (Roscoe et al., 2019; Martinsuo & Luomaranta, 2018). The findings have not suggested the full impact of AM integration on existing operational practices.

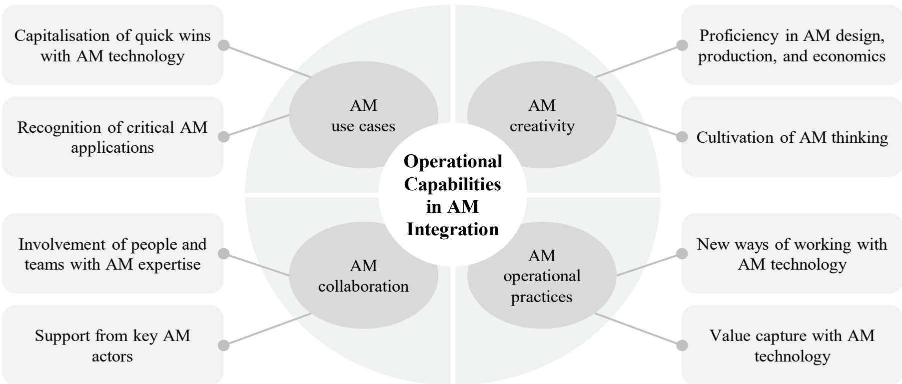

Figure 3 *Operational Capabilities in AM Integration*

5.2.2 Essential Actions to Overcome the Additive Manufacturing Integration Challenges with Operational Capabilities

The findings from the Strategy and Tactics study, the Gearbox study, and the Learn from Others study, revealed several short-term and long-term essential actions to overcome the challenges with operational capabilities throughout a four-stage AM integration process (see **Figure 4**).

Short-term essential actions are actions that the global heavy vehicle manufacturer has performed before or can perform today in current and upcoming AM integration projects starting within one year. In the need stage, *short-term acquisition and building of AM use cases are required to overcome ambiguous* *ownership* (Paper III). This action enabled the workforce to determine whether AM could address the specific needs of the global heavy vehicle manufacturer by mainly relying on external operational capabilities. For instance, the identification of suitable low-volume AM spare parts using certain AM polymers was provided by an external AM supplier and initiated by the Purchasing department. AM spare parts with certain AM polymers sourced from different external AM actors might be produced using different AM machines, thereby gaining different surface finishes and different material properties at varied costs (Luomaranta & Martinsuo, 2022). In the pre-integration stage, *short-term acquisition and building of AM creativity is required to overcome cognitive fixation* (Paper III). This action can enable the workforce to secure relevant capabilities to succeed or fail with AM integration by mainly relying on external operational capabilities. For instance, departments can hire consultants with knowledge and experience in AM or purchase services from AM actors. In the integration stage, *short-term acquisition and building of AM collaboration are required to overcome situational awareness* (Paper III). This action enabled the workforce to ensure the successful and consistent realisation of a working order with AM technology by mainly relying on external operational capabilities. For instance, the production of low-volume AM spare parts using certain AM polymers was conducted by an external AM supplier and initiated by the Purchasing department on an on-demand basis. It is important to leverage external AM actors that possess post-processing capabilities to avoid leveraging additional internal post-processing capabilities or other additional external AM actors (Chaudhuri et al., 2019). In the post-integration stage, *short-term acquisition and building of AM operational practices are required to overcome manufacturing fixation* (Paper III). This action can enable the workforce to apply continuous improvements of business and technical-related activities with AM technology by mainly relying on external operational capabilities. For instance, departments can utilise online free of charge software, purchase new, or upgrade existing CAD, CAE, and CAM software with AM-based applications. The choice of software needs to be suitable for the design and production of certain products, such as heavy vehicles (Yi et al., 2019; Deradjat & Minshall, 2017).

Long-term essential actions are actions that the global heavy vehicle manufacturer can perform in future AM integration projects starting after three years. In the need stage, *long-term building and learning of AM use cases is required to overcome ambiguous ownership* (Paper III). This action can enable the workforce to determine whether AM can address the specific needs of the global heavy vehicle manufacturer by mainly relying on internal operational capabilities. For instance, the identification of suitable high-volume AM spare parts using certain AM polymers or metals as well as AM production can be conducted in-house by the Purchasing and Operations departments respectively. Transitioning from short-term acquiring and building to long-term building and learning of AM use cases requires extensive knowledge and experience in AM and investments in specific in-house AM machines that address the specific needs of the global heavy vehicle manufacturer (Friedrich et al., 2022a; Chaudhuri et al., 2019; Martinsuo & Luomaranta, 2018). In the pre-integration stage, *long-term building and learning of AM creativity is required to overcome cognitive fixation* (Paper III). This action can enable the workforce to secure relevant capabilities to succeed or fail with AM integration by mainly relying on internal operational capabilities. For instance, the workforce should opt into AM education and training programs provided either in-house or by an external AM actor. Investing in AM creativity will expand the workforce's capacity to explore and exploit new opportunities such as designing for AM, new AM supply chains, and enabling product customisation (Klahn et al., 2020; Fontana et al., 2019). In the integration stage, *long-term building and learning of AM collaboration to overcome situational awareness* (Paper III). This action can enable the workforce to ensure the successful and consistent realisation of a working order with AM technology by mainly relying on internal operational capabilities. For instance, manufacturing AM production tools in metal AM material and in-house serial production of AM spare parts and AM products can be conducted in-house by the Operations department through requests by the Purchasing and Technology departments. Transitioning to in-house AM production can be facilitated through collaboration with non-profit organisations, academia-industry centres, and other AM collaboration networks (Stentoft et al., 2021; Chaudhuri et al., 2019; Martinsuo & Luomaranta, 2018). In the post-integration stage, *long-term building and learning of AM operational practices is required to overcome manufacturing fixation* (Paper III). This action can enable the workforce to apply continuous improvements of business and technical-related activities with AM technology by mainly relying on internal operational capabilities. For instance, departments can involve AM actors when setting up a new way of working with certain AM technology in-house. Transitioning to in-house AM operational practices will have a certain impact on existing capabilities (Rylands et al., 2016). Applying these changes to existing capabilities depends on the overall strategy of the global heavy vehicle manufacturer and the need to be competitive with AM in the heavy vehicle market (Friedrich et al., 2022a; Öberg & Shams, 2019).

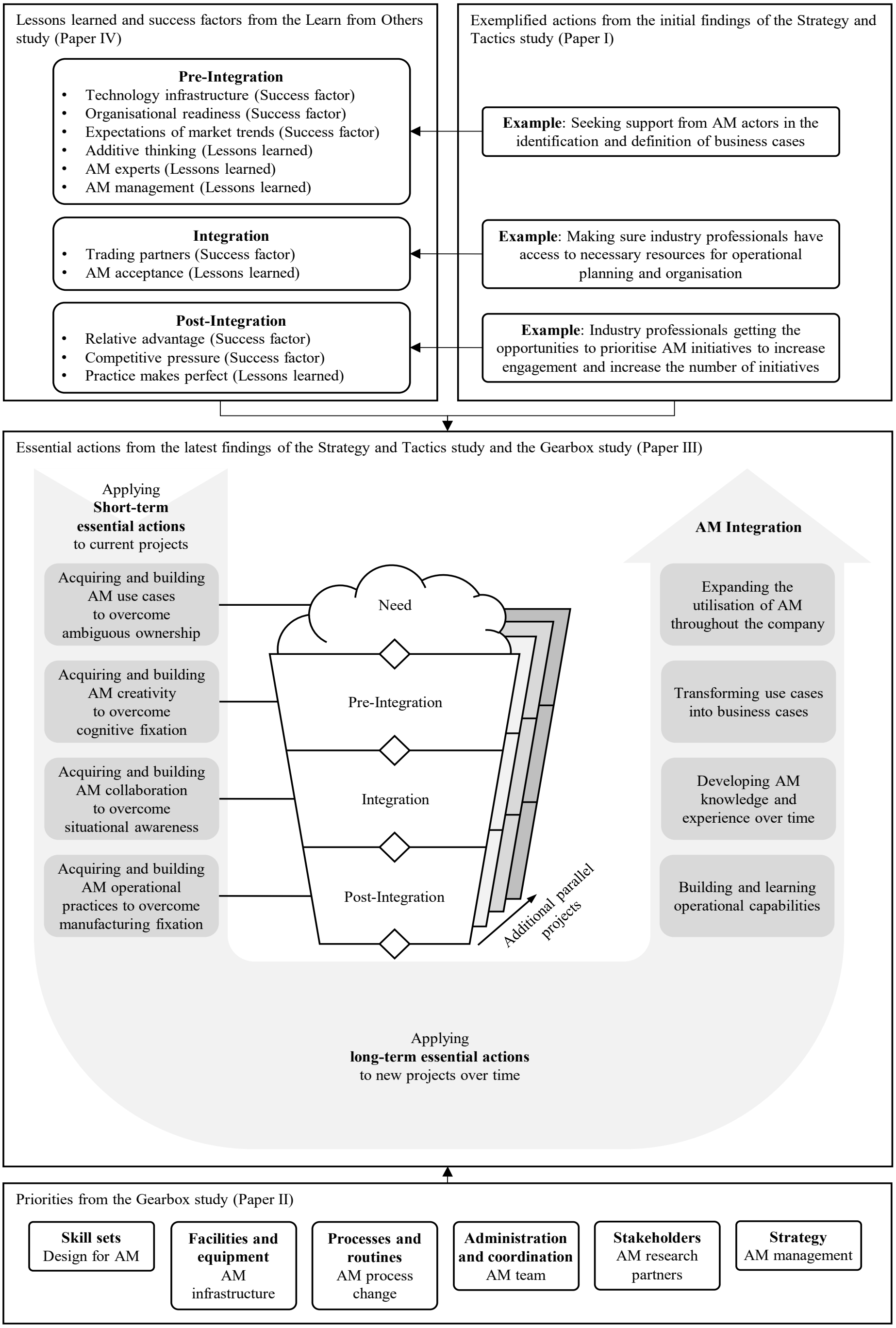

Figure 4 *Facilitation framework for overcoming the AM Integration Challenges with Operational Capabilities*

Moreover, the global heavy vehicle manufacturer should consider the success factors and lessons learned from other manufacturing companies that underwent a similar AM integration journey. In the pre-integration stage, other manufacturing companies saw success from having technology infrastructure, organisational readiness, and expectations of market trends. However, they learned that it was imperative to have additive thinking, AM experts, and AM management in-house (Paper IV). For instance, it is important to seek support from AM actors when identifying and defining AM business cases (Paper I). In the integration stage, other manufacturing companies saw success from having trading partners, such as service providers and machine providers, and learned to increase the AM acceptance throughout the company (Paper IV). For instance, the workforce need to have access to the necessary capabilities for operational planning and organisation of a working order with AM (Paper I). Lastly, in the post-integration stage, other manufacturing companies saw success from having a relative advantage and competitive pressure with AM. On the other hand, they learned that practice makes perfect, emphasising on failing early and often (Paper IV). For instance, the workforce should get the opportunity to prioritise AM initiatives to increase their engagement and increase the number of initiatives throughout the company. The findings from the Gearbox study suggested that to succeed with AM integration based on the gearbox use case, the next steps should prioritise design for AM, AM infrastructure, AM process change, AM team, AM research partners, and AM management (Paper II). These priorities share similarities with the identified success factors and lessons learned.

5.3 Scientific Implications

Scientific implications are pointed out through the following insights. *First, AM integration challenges*. The initial 20 AM integration challenges confirmed similarities with previous research (see for example Mellor et al., 2014) but lacked significant novelty. Later, cognitive fixation and manufacturing fixation shared similarities with previous research (see for example Yi et al., 2019). However, ambiguous ownership and situational awareness stand out from the global heavy vehicle manufacturer and have not been recorded in the AM literature. *Second, operational capabilities in AM integration*. The initial 57 operational capabilities confirmed similarities with previous research (see for example Friedrich et al., 2022a, 2022b; Deradjat & Minshall, 2017) but lacked significant novelty. Later, three of the four operational capabilities, namely AM creativity, AM collaboration, and AM operational practices shared similarities with previous research (see for example Luomaranta & Martinsuo, 2022; Stentoft et al., 2021; Martinsuo & Luomaranta, 2018). However, AM use cases stand out due to the heavy vehicle sector and have not been recorded in the AM-based operational capability literature. *Third, an* *extension of existing frameworks in the literature*. The initial findings from the Strategy and Tactics study suggested the extension of an existing AM integration framework (Mellor et al., 2014) with a seventh dimension namely added value. Additionally, the latter findings from the Strategy and Tactics study and the Gearbox study suggested the extension of an existing technology-organisation-environment-value-risk framework (Priyadarshini et al., 2022) with three additional factors namely usage, tradition, and image. Moreover, the initial findings from the Gearbox study suggested two additional dimensions, namely stakeholders and strategy (Teece, 2019; Teece et al., 1997). Thereby, extending the existing operational capability framework (Teece, 2019; Wu et al., 2010), and initially confirming dynamic capabilities (Teece, 2019; Teece et al., 1997). *Fourth, the utilisation of a simplified integration process*. The latter findings from the Strategy and Tactics study and the Gearbox study suggested the extension of an existing three-stage integration process (Voss, 1988) with a fourth stage, namely the need stage (Andreasen & Hein, 1987). Despite efforts from previous research to map AM integration challenges in similar three-stage integration processes (see for example Chaudhuri et al., 2019; Deradjat & Minshall, 2017), previous research has not mapped operational capabilities throughout the four-stage integration process. *Fifth, essential actions to overcome the AM integration challenges with operational capabilities*. The latter findings from the Strategy and Tactics and the Gearbox studies suggested the emergence of short-term and long-term essential actions to overcome the AM integration challenges with operational capabilities. The short-term and long-term essential actions share similarities with previous research (see for example Friedrich et al., 2022a) that investigated make-or-buy decision-making. However, the AM literature has not investigated operational capabilities as a specific solution to AM integration challenges. Thereby, this highlights novel findings that contribute to the ongoing discourse in the AM operational capability literature (Roscoe et al., 2019; Holmström et al., 2017). The findings also suggested that it is imperative that manufacturing companies share their success and lessons learned with each other which was confirmed by previous research (Martinsuo & Luomaranta, 2018; Yeh & Chen, 2018).

5.4 Managerial Implications

The following insights are implications for management to consider. *First, AM integration challenges*. Managers across several departments share responsibility in identifying and providing solutions to overcome AM integration challenges. *Second, operational capabilities in AM integration*. Today, manufacturing companies that have started their AM integration journey have incorporated some operational capabilities. Managers should extend existing operational capabilities and develop new ones, preferably in collaboration with external AM actors. *Third, an extension of existing frameworks in the literature*. The extended AM integration framework, the extended technology-organisation-environment-usage-value-risk-tradition-image framework, and the extended operational capability framework showcase a holistic and complex overview of AM integration in an industrial setting. Managers need to consider that AM integration will introduce a wide variety of changes to existing capabilities throughout the company. *Fourth, the utilisation of a simplified integration process*. The AM integration process can be simplified which was shown in this research. However, managers need to be aware that AM integration is complex and should use the four-stage integration process after careful reflection in industrial settings. *Fifth, essential actions to overcome the AM integration challenges with operational capabilities*. The identified short-term and long-term essential actions to overcome the AM integration challenges with operational capabilities should be used as guidance for managers across several departments. This will help to map the current situation and propose ways of moving forward with AM integration. Additionally, managers should seek support from other manufacturing companies or AM actors to facilitate AM integration.

6 Conclusion

This chapter concludes the key takeaways of this thesis highlighting various contributions, research methodology implications and limitations, and recommendations for future research.

6.1 Concluding Remarks

The purpose of this thesis is to explore the integration of AM into the manufacturing industry. The main contributions of this research are listed below.

1. Manufacturing companies, including the global heavy vehicle manufacturer, find AM integration challenging due to ambiguous ownership, cognitive fixation, situational awareness, and manufacturing fixation.
2. Manufacturing companies, including the global heavy vehicle manufacturer, should secure the required operational capabilities such as AM use cases, AM creativity, AM collaboration, and AM operational practices.
3. Manufacturing companies, including the global heavy vehicle manufacturer, should incorporate short-term and long-term essential actions to overcome the AM integration challenges with operational capabilities to take the next steps with AM integration.
4. This research extended existing frameworks in the literature including the existing AM integration framework, the existing technology-organisation-environment-value-risk framework, and the existing operational capability framework.
5. There is a need to have awareness that AM integration is more complex in industrial settings despite efforts from previous research to simply AM integration. It is suggested to seek support from other manufacturing companies and AM actors.

6.2 Research Methodology Implications and Limitations

Conducting research can be a bit difficult and the following implications and limitations were encountered in this thesis.

The *research approach* showed that I had to switch between several roles making it difficult, and at certain times impossible, to determine when certain findings emerged throughout the research process. This was mitigated by adopting a reflective view allowing frequent careful thinking throughout the research process.

The *research design* may have been influenced by certain biases due to the early involvement by and collaboration with a single global heavy vehicle manufacturer. The main benefit was the ability to gain interesting and relevant empirical insights on AM integration with access to certain facilities, project opportunities, informal meetings, and daily interactions with industry professionals. On the other hand, this may have been a limitation by not including insights from other manufacturing companies. To mitigate this limitation the Learn from Others study was included.

The *research process* was challenging due to me being (and still being) the only AM expert at the global heavy vehicle manufacturer, limiting the fruitful AM-related discussions throughout the research process. This was mitigated by launching the Learn from Others study, immersing myself into national and international AM-based doctoral student networks as well as AM-based research communities, and frequently having informal meetings with various national and international AM actors.

The *data collection* initially considered a limited number of participants working in management and engineering roles and involvement in studies from a single global heavy vehicle manufacturer. This limitation was mitigated by the Learn from Others study which considered insights from other companies besides the global heavy vehicle manufacturer. Moreover, the current insights from the Learn from Others study might be affected by bias since the data was published as customer stories by three AM actors. Additional studies involving the global heavy vehicle manufacturer and other AM actors should mitigate these limitations as part of future research.

The *data analysis* mainly focused on interpreting findings, based on qualitative data, using thematic analysis. With the addition of the Gearbox study and the Learn from Others study, quantitative data has been included. Grounded theory or other qualitative and quantitative data analysis methods could be interesting to use as part of future research.

The *research quality* could be improved by enhancing the generalisation of the findings and transferability to other contexts and sectors. Certain generalisation tactics could be emphasised more in future studies. Even though the findings are transferable to other contexts and sectors, researchers and industry professionals need to critically reflect before applying the findings.

Transferability can be improved by providing rich and detailed descriptions of the contexts and sectors as part of future research.

The *ethical considerations* could be improved in the upcoming studies by continuing to reduce subjectivity (e.g., iterate findings with participants more frequently) and use confidential information (if relevant) throughout the whole data analysis process.

6.3 Recommendations for Future Research

AM integration is still an ongoing journey for the global heavy vehicle manufacturer and other manufacturing companies that share similarities. Therefore, the following recommendations for future research are suggested.

1. Evaluate and test the facilitation framework and map AM integration challenges and operational capabilities of critical heavy vehicle AM use cases.
2. Explore the technical opportunities and limitations and the make-or-buy decision-making scenarios in AM integration of critical heavy vehicle AM use cases.
3. Explore operational capability and dynamic capability theories in AM integration of critical heavy vehicle AM use cases.
4. Explore the transition from an AM use case to an AM business case in the heavy vehicle manufacturing industry.
5. Explore the AM integration journeys of manufacturing companies in other sectors regarding technical opportunities and limitations, make-or-buy decision-making, and transition from an AM use case to an AM business case, for example.

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Appendix

Contents

Appendix A – Focus group design and questions for the Strategy and Tactics study

Focus group session 1

- Round table introductions by all participants.
- What is the status of AM in the company? (Round table presentations)
- What challenges and barriers do you see when integrating AM into the company? (Group discussion, 3-5 participants in each group)
- Why has AM not progressed or matured enough within the company? (Group discussion, 3-5 participants in each group)

Focus group session 2

- Round table introductions by all new participants.
- Has anything new related to AM happened since last time. What is the status of AM in the company? (Round table presentations)
- A map of the challenges from the previous focus group session and additional findings was presented to the focus group.
- What mitigation actions or solutions do you see to overcome the challenges? (Group discussion, 3-5 participants in each group)
- What operational capabilities do you see are required to overcome the challenges? (Group discussion, 3-5 participants in each group)

Focus group session 3

- All identified challenges and operational capabilities were summarised and presented to the focus group.
- The participants were asked to do matchmaking, meaning selecting which operational capabilities were best suited to overcome the challenges. (Group discussion, 3-5 participants in each group)

Appendix B – Interview guide for the Gearbox study

Introduction

- What is your name?
- What is your current job role?
- How many years have you had this position?
- How many years have you worked at the global heavy vehicle manufacturer?

The following design questions were asked of those working with design.
Designing of gears /shafts

- What are the important mechanical properties and material properties of a gear/shaft?
- What are the common load cases for a gear/shaft?
- Which materials are commonly used for gears/shafts?
- How do you design gears/shafts? What are the general activities step-by-step?
- Do you see a need to change the current design of the gears/shafts?
    - If yes, what changes would you suggest?
    - If not, why not?
- What input would you need to refine the new design of the gears/shafts? From whom do you need input? Internal, external, or both?
- What needs to be evaluated in the new design of the gears/shafts before moving to (final) production?
    - What are the design criteria?
- Do you use any "design for X" guidelines for gears/shafts?
    - If yes, what "design for X" guidelines do you use?
    - If not, why not?
- What kind of competence, know-how, or skill set do you think is needed to design gears/shafts with current production systems?
- What do you think will change in the design of new gears/shafts in the near future?
- Do you think it is possible to design gears/shafts with AM?

- If yes, how?
- If not, why not?

The following production questions were asked of those working in production.

Production of gears/shafts

- What are the important aspects to consider when producing gears/shafts?
- How do you prepare the production system for gears/shafts now? For example, who sets up the production planning?
- How do you produce gears/shafts? What are the general activities step-by-step?
- Do you see a need to change the current production process/system of gears/shafts?
  - If yes, what changes would you suggest?
  - If not, why not?
- What input would you need to refine the new production process/system of the gears/shafts? From whom do you need input? Internal, external, or both?
- What needs to be evaluated in the new production system of the gears/shafts before moving to (final) production?
- What kind of competence, know-how, or skill set do you think is needed to develop a new production system for gears/shafts?
- What do you think will change in the production system of new gears/shafts in the near future?
- Do you think it is possible to produce new gears/shafts with AM?
  - If yes, how?
  - If not, why not?

The following interface questions were asked of all participants.

Interface Design and Production

- How are the people from production engaged in the development phase of designing gears/shafts?
- Do you see any specific barriers or challenges in the involvement of people from production in the development phases of designing gears/shafts?
- Do you see any specific opportunities or benefits in the involvement of people from production in the development phases of designing gears/shafts?
- How can we improve collaboration and increase engagement between people from both design and production in the development phase of designing gears/shafts?

- How are the people from design engaged in the development phase of the production system for gears/shafts?
- Do you see any specific barriers or challenges in the involvement of people from design in the development phase of the production system for gears/shafts?
- Do you see any specific opportunities or benefits in the involvement of people from design in the development phase of the production system for gears/shafts?
- How can we improve collaboration and increase engagement between people from both design and production in the development phase of the production system gears/shafts?

If AM is an available production method

- Does your current work role include activities regarding AM?
  - If yes, what are/were your activities?
  - If not, why not?
- What is your current knowledge level regarding AM?
  - Superior knowledge (5)
  - Adequate knowledge (4)
  - Basic knowledge (3)
  - Minimal knowledge (2)
  - No knowledge (1)
- Do you know if your company has an AM strategy?
  - If yes, do you have any goals related to the design and production of gears/shafts? What activities are you currently doing that are related to the goals?
  - If not, what goals would you like to have related to the design and production of gears/shafts? What activities would you suggest having related to the goals?
- What opportunities or benefits do you see with AM when designing and producing gears/shafts?
- What barriers or challenges do you see with AM when designing and producing gears/shafts?

SHOW CONCEPTS OF THE GEARS/SHAFTS

General questions regarding the design of the concepts

- What benefits do you see in the concepts in terms of design?
- What challenges do you see in the concepts in terms of design?
- What changes would you propose in the concepts in terms of design? What are the activities?

- Based on your current level of AM knowledge and work situation, what competence, capacity, or resources do you think are missing to design the concepts for AM?

General questions regarding production of the concepts

- What benefits do you see in the concepts in terms of production?
- What challenges do you see in the concepts in terms of production?
- What changes would you propose in the concepts in terms of production? What activities would you suggest?
- Based on your current level of AM knowledge and work situation, what competence, capacity, or resources do you think are missing to produce the concepts with AM?

SHOW THE CONCEPT OF THE COMBINED GEARS AND SHAFT SYSTEM AND USE THE SAME GENERAL QUESTIONS FOR THE CONCEPTS

Part II
The appended papers

The appended papers included in this thesis are removed in the publicly online version due to copyright reasons. However, they are included in the physically printed book.