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From design to operations

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MATRIX-STRUCTURED MANUFACTURING SYSTEMS: FROM DESIGN TO OPERATIONS

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Dissertation Background

This introductory information serves the purpose of preparing the readers of this PhD dissertation. This small section therefore provides the reader with a brief introduction to the kappa and the overall dissertation, and a clear definition of the key term, Matrix-Structured Manufacturing Systems. Furthermore, this section also introduces essential works that are beneficial to read prior to continuing reading the remaining sections, while finally, an overview of the published works are briefly introduced to highlight essential parts of the academic contributions that this PhD dissertation has reached.

This PhD dissertation consists of two aspects; a *kappa* – a comprehensive summary of the relevant contributions performed throughout the PhD study – as well as an appendix, containing the published and submitted publications connected to the dissertation. The kappa consists of six main chapters; Introduction, Theoretical Background, Research Design, Results, Discussion, and Conclusion. These chapters combined summarize and emphasize the contributions throughout the PhD study. These chapters, respectively, present the research questions and motivation therefore, the academic state-of-the-art, the research design and methodology to investigate the research questions, the findings thereof, a discussion and reflection of the results as well as potential research directions that was not investigated throughout the PhD study, and finally a conclusion that answers the research questions, focus on the managerial and academic contributions, and future research. Thereafter, the appendix presents the published and submitted publications that is connected to the contributions in the kappa. In addition to the publications in the appendix, co-authorstatements for these are also presented.

A central term used throughout the kappa is “Matrix-Structured Manufacturing Systems”. It is therefore crucial to provide a definition prior to reading the kappa. In this kappa, “Matrix-Structured Manufacturing Systems” are defined, in it’s simplest form, as follows:

A manufacturing system consisting of flexible and reconfigurable, standardized work cells, typically structured with a matrix-like topology. The intralogistic transportation between the work cells is realized through flexible means of transportation. The manufacturing system is dynamically adaptable to internal and external conditions.

While this definition is indeed broad, it provides a general abstracted overview of the term and concept. Throughout the kappa and the appended publications, more specific details related to typical implementations are presented thus contributing with a more narrow definition, for example by detailing the intralogistics material flow tools, work cell designs, dynamic control system and architecture, and similar. In this regard, it is highly recommended to read the publications by (Greschke *et al.*, 2014; Schönemann *et al.*, 2015) to further strengthen the preliminary knowledge before continuing reading the kappa and appended publications.

Appended to the kappa, four publications can be found, following the naming convention “Paper A”, “Paper B”, etc. An overview of the works related to this dissertation can be found on page ii in the appendix. Co-author statements can be found, starting on page xxxv.

Abstract

In recent years, the need for more flexible manufacturing systems has increased. This is caused by the consumers' increasing demand for more individualized products at a low price point. To achieve this, the manufacturing companies must be able to produce the products with a high variety and high production volume. This requires a multitude of flexibility types, such as product flexibility, control program flexibility, material handling flexibility, and similar. One of the manufacturing system paradigms that address these types of flexibility, is *Matrix-Structured Manufacturing Systems*, also often denoted simply *Matrix Production*.

Matrix-Structured Manufacturing Systems consist of reconfigurable, standardized work cells, typically scattered in a matrix pattern, with a flexible non-linear material flow between the work cells. This material flow is typically enabled by automatic guided vehicles or autonomous mobile robots. As the work cells, depending on the tool configuration, can perform multiple work packages, they enable redundancy, parallel manufacturing of different products and product families, as well as upscaling and downscaling of the production throughput.

The current literature on this type of manufacturing system is though primarily focused on the design of the manufacturing system and critical components of it, such as control of the automatic guided vehicles. This means that the current literature does not address the transition from design to operations of this manufacturing system. This research gap is addressed in this PhD dissertation, where it investigates:

1) How Matrix-Structured Manufacturing Systems facilitate flexibility,
2) How to design Matrix-Structured Manufacturing Systems, and
3) How to control Matrix-Structured Manufacturing Systems

These research questions are answered using respectively a systematic literature review, a laboratory case study, and two company case studies. The results from these methodologies yield, among others, two approaches to design both the work cells and products within this type of manufacturing system. To fully benefit from the increased flexibility from this manufacturing system, a control system architecture targeted Matrix-Structured Manufacturing Systems is furthermore developed.

Based on the results from the research questions, Matrix-Structured Manufacturing Systems are discussed in relation to a supply chain perspective. This perspective pays special attention to the resilience that is both enabled and required, when implementing this type of manufacturing system. Additionally, a sustainability perspective is discussed in connection with the supply chain perspective. Finally, Matrix-Structured Manufacturing Systems are discussed as an enabler for new business opportunities, such as Manufacturing-as-a-Service. With this foundation, a discussion and reflection on Matrix-Structured Manufacturing Systems as a manufacturing system of the future is presented.

Resumé

I løbet af den seneste årrække, er behovet for mere fleksible produktionssystemer steget markant. Dette skyldes forbrugernes øgede efterspørgsel efter individualiserede produkter til en lav købspris. For at produktionsvirksomhederne kan realisere dette, skal de både kunne producere meget individualiserede produkter, samt i et højt styktal. Dette kræver forskellige typer af fleksibilitet, såsom produktfleksibilitet, kontrolprogramsfleksibilitet, materialeflowsfleksibilitet og lignende. Ét af de produktionsparadigmer, der addresserer flere af disse typer fleksibilitet, er *Matrix-Structured Manufacturing Systems*, også på dansk typisk kaldet *Matrix Produktion*.

Matrix Produktion består fundamentalt af rekonfigurerbare, standardiserede produktionsceller, typisk struktureret i en matrix, med et fleksibelt ikkelineært materialeflow imellem, oftest realiseret af selvkørende robotter. Idet produktionscellerne, alt afhængig af deres konfiguration af værktøj, kan udføre flere arbejdspakker, dannes der rammerne for redundans, parallel produktion af forskellige produkter og produktfamilier, samt op- og nedskalering af disses produktionsvolumen.

Den nuværende literatur om Matrix Produktion er dog primært centreret omkring designet af produktionssystemet, samt kritiske komponenter deraf, såsom styringsalgoritmer til de selvkørende robotter. Der er imidlertid ikke fokus på produktionssystemets transition fra design til implementering. Denne mangel i den nuværende literatur addresseres af denne PhD afhandling, idet den besvarer hvorledes:

1) Matrix Produktion faciliterer fleksibilitet,
2) Matrix Produktion designes, samt
3) Matrix Produktion bedst styres.

Disse forskningsspørgsmål bliver besvaret ved brug af henholdsvis en systematisk literaturgennemgang, efterfulgt af et laboratoriebaseret casestudie, samt to virksomhedscasestudier. Resultaterne deraf udmunder blandt andet i to metodiske tilgange til at designe produktionscellerne i en Matrix Produktion, samt produkterne der skal produceres deri. For at få fuldt udbytte af den øgede fleksiblitet, er der også udviklet en dedikeret kontrolsystemsarkitektur til Matrix Produktion.

Baseret på disse resultater, diskuteres Matrix Produktion, set i forhold til et forsyninskædeperspektiv med øget fokus på dennes robusthed og hvordan Matrix Produktion båder afhænger af og øger denne. Ydermere diskuteres Matrix Produktion i forhold til et bæredygtighedsperspektiv, der også sammenholdes med forsyningskæderobustheden. Sidst, men ikke mindst, med fodfæste i disse perspektiver, diskuteres det hvorledes Matrix Produktion danner grobund for nye forretningsmuligheder, for eksempel andelsproduktion. På den baggrund opsummeres diskussionen med en reflektion om Matrix Produktion som fremtidens produktionssystem.

Acknowledgements

Throughout my time at University of Southern Denmark, and especially my years as a PhD student, I have encountered many people that deserve a special ‘thank you’ for the kind support and guidance, the never-ending learnings, and the deep and sometimes challenging reflections.

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A deep thank you to my current and former colleagues for the always positive atmosphere, and for a smooth transition from student to colleague. It has been a pleasure and inspiration to work with every single one of you. My old ‘desk-buddy’ Dr. Grube Hansen also deserves a big thank you for the good talks and discussions. I am deeply honored to have gotten the opportunity to work with such skilled, knowledgeable, and generally good people.

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A special thank you goes out to my family-in-law for their kindness and support. I am very grateful for the pleasant and relaxed atmosphere around you, as well as all the unconditional help, especially during the last year of the dissertation.

Many thanks to my parents for the unlimited love, support, and belief in me. Thank you to my sister for being who you are and always ready to help. Also a great thanks to my grandparents here and beyond.

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Last but not least, I would like thank my committee members for spending your valuable time reading and evaluating this project. I hope you will enjoy reading the revised dissertation and that it might spark an interest for future collaboration. I am grateful for the time and effort you have put into providing the thorough comments and suggestions to improve the quality of the dissertation – thank you!

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Abbreviations

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AMM	Autonomous Matrix Manager
AMR	Autonomous Mobile Robot
BCG	Boston Consulting Group
BoM	Bill of Materials
BoP	Bill of Processes
CAD	Computer-Aided Design
CIRP	Collège International pour la Recherche en Productique
CMS	Changeable Manufacturing System(s)
CNC	Computer Numerical Control
COM	Component Object Model
DES	Discrete Event Simulation
DfX	Design for X
DML	Dedicated Manufacturing Line
DT	Digital Twin(s)
ERP	Enterprise Resource Planning
FFMS	Focused Flexibility Manufacturing System(s)
FMS	Flexible Manufacturing Systems
HMHV	High Mix High Volume
HMLV	High Mix Low Volume
IJIDeM	International Journal on Interactive Design and Manufacturing
JSON	JavaScript Object Notation
LMHV	Low Mix High Volume
MaaS	Manufacturing-as-a-Service
MC	Matrix Controller
MES	Manufacturing Execution System
ML	Machine Learning
MLP	Multi Layer Perceptron
MMS	Matrix-Structured Manufacturing System(s)
NASA	National Aeronautics and Space Administration
OEE	Overall Equipment Efficiency
PhD	Doctor of Philosophy
PLM	Product Lifecycle Management
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RMS	Reconfigurable Manufacturing System(s)
RMT	Reconfigurable Machine Tool(s)
RO	Research Objective
RQ	Research Question
SC	Supply Chain(s)
SCADA	standardized supervisory control and data acquisition
SCRES	Supply Chain Resilience
SDG	Sustainable Development Goal(s)
SDU	University of Soutern Denmark
SLR	Systematic Literature Review
SME	Small and Medium-Sized Enterprise(s)
UN	United Nations

1. Introduction

1.1 Motivation

This dissertation focuses on Matrix-Structured Manufacturing Systems (MMS), also often denoted “Matrix Production”, and the flexibility that these manufacturing systems posses. This manufacturing system enables a scalable, adaptable, resilient, and redundant solution that not only can produce a wide variety of products but also in a high volume. At the same time, MMS can easily adapt to either new product variants or even new product families. This expands the lifetime of the manufacturing system and increases resilience which has been ever more important with the previous year's unfortunate events, such as the pandemic, raw material shortage, armed conflicts, war, etc. However, these benefits of MMS are not easily obtainable with the current knowledge and approaches. To expand the current knowledge and approaches, company and laboratory case studies have been applied using simulations and Digital Twins (DT). These technologies have in recent years gained in popularity and even been considered enablers of respectively the fourth and fifth industrial revolutions (Rüßmann *et al.*, 2015; Müller, 2020). The motivation for carrying out this dissertation is therefore to investigate how MMS and flexibility relate to the factory of the future using technologies such as Digital Twins and simulation. As this manufacturing system shows promising results in relation to resilience in a mass customization perspective, the MMS paradigm addresses challenges in the near future for the manufacturing domain.

1.2 Background

In recent years, the need for more customizable products has increased. Customers and users request more personalized products that can be customized to their specific needs or specifications while maintaining a relatively low price (Da Silveira, Borenstein and Fogliatto, 2001; Liu, Tian and Kan, 2022). This statement is further supported by the tendency to shorten the product life cycle (Gaimon and Singhal, 1992; Pérez-Pérez *et al.*, 2018), meaning customers are requesting customizable products faster for a lower cost. Additionally, demand uncertainties of products from the possible rapid market changes further challenge the manufacturing companies (Vafadar, Tolouei-Rad and Hayward, 2017). Therefore it can be discussed that, as Bossen et al. summarize from a manifesto, “the era of Mass Production is over” (Bossen *et al.*, 2014).

However, mass customization – the successor to mass production – introduces new challenges in the manufacturing domain. Where traditional line productions are tailored to produce specific products in high volumes, other manufacturing system paradigms have been proposed to address the challenge of balancing the product variety and the product volumes. These paradigms, such as Flexible Manufacturing Systems (FMS), Focused Flexibility Manufacturing Systems (FFMS), Cellular Manufacturing Systems, and Changeable Manufacturing Systems (CMS), all provide solutions in different approaches. However, common for all is that an increase in product variety yields a decrease in production volume (ElMaraghy *et al.*, 2013). With this decrease in production volume, the frequent costs of changeovers to new products, and the initial higher investment costs (Gaimon and Singhal, 1992), the manufacturing system life cycles are typically prolonged to be economically sustainable for the manufacturing companies (Andersen *et al.*, 2017).

The key factor in manufacturing systems addressing product variety is *flexibility*. In the pursuit of manufacturing flexibility, it is important to identify that the term covers both different types of flexibility as well as different levels. ElMaraghy summarizes 10 types of flexibility (ElMaraghy, 2005) that depending on the technologies implemented to enable these types of flexibility can yield different levels. This is further elaborated on in section 2.1. As the different manufacturing system paradigms address different types of flexibility and at different levels, it is crucial to take the selection of manufacturing system paradigms into account when new challenges, such as mass customization, arise in the manufacturing domain.

A manufacturing system paradigm that enables many types of flexibility in high levels, is MMS. In this way, the manufacturing system is capable of addressing the challenges of mass customization. A limitation of flexibility is though the increased complexity connected with the design, control, and general operation of it. With this increased complexity, new challenges arise that have not been addressed in a similar manner with the existing manufacturing system paradigms.

To address these challenges, technological development, especially in the digital manufacturing domain, aids the exploration, decision-making, development, and operation of these manufacturing system paradigms. Especially simulation enables both an explorative, qualitative dimension as well as a performance evaluating, quantitative dimension (Eldabi *et al.*, 2002). A limitation of simulation, in general, is the verification and validation of the data input and output. Recent technological developments, such as DT allows for directly measuring the impact of changes and verifying and validating the data, by creating a bi-directional communication between the physical system and the simulation model. In this way, simulation and DT can become a crucial tool to investigate flexibility and operationalize a manufacturing system paradigm.

To stress the pain point for the research objective and connected research questions, it can be highlighted that difficulties in addressing the need for more flexible manufacturing systems that deal with mass customization and more personalized products, produced in shorter product life cycles and with much higher demand uncertainties and fluctuations exist (Nielsen *et al.*, 2023). This challenge can be addressed in several ways, for example by combining emerging technologies to existing manufacturing system paradigms, like implementing Automatic Guided Vehicles in cellular manufacturing systems (Dehnavi-Arani, Saidi-Mehrabad and Ghezavati, 2019). However, elaborating on the current literature on MMS, for example (Schönemann *et al.*, 2015; Trierweiler, Foith-Förster and Bauernhansl, 2020; Schumacher, Weckenborg and Spengler, 2022), there is no clear overview *how* MMS can address this pain point through flexibility it facilitates. Secondly, the flexibility of a manufacturing system can be enabled through multiple means, depending on the paradigm, and thus aspects like topology, equipment, etc. It is therefore crucial to investigate how to design MMS to fully leverage the benefits of these facilitated types of flexibility. While the current literature focus on the holistic system-level design and intralogistics of MMS (Fries, Wiendahl and Assadi, 2020; Schumacher, Weckenborg and Spengler, 2022), there is however a huge untouched potential in the less abstracted work cell and product design for MMS in regards to flexibility and optimization of performance. Last but not least, it can be deduced that the control of MMS influence partially the flexibility aspects of MMS, as well as the performance of the manufacturing system paradigm. While the current literature address these points to a certain degree (Li *et al.*, 2021; Zhang *et al.*, 2022), a more holistic control system architecture is needed to fully operationalize MMS and enable the full palette of flexibility types that this manufacturing system paradigm enables.

1.3 Research Questions

The purpose of this dissertation is to explore how to operationalize MMS. Where current literature focuses primarily on the design of MMS or the material flow therein (Schönemann *et al.*, 2015; Filz *et al.*, 2019; Schumacher, Weckenborg and Spengler, 2021), little efforts have been made on the transition from manufacturing system design to the operationalization. As MMS differ from current manufacturing system paradigms, due to the multitude of flexibility types it enables, the present approaches to operationalize a manufacturing system cannot fully leverage the benefits of MMS in an efficient manner. Therefore, to transition from the design phase to the operations phase, it is important to consider several steps. These steps, condensed into three research questions (RQ), address the research objective (RO). An overview of this can be found in Figure 1. It is crucial to highlight that in this kappa, operationalization is regarded as the process from design to operations.

The first RQ therefore investigates how MMS facilitate flexibility. This step is crucial, as it provides a foundation partly for understanding the enabling aspects of the manufacturing system, and partly how to maximize the flexibility in the design and control phase of the operationalization. This foundation furthermore puts MMS as a paradigm into perspective to the other manufacturing system paradigms, as it highlights how it differs. In this way, the RQ provides a perspective to the adoption of this paradigm compared to other paradigms that similarly enable flexibility.

The second RQ explores how to design a MMS with particular attention to the MMS work cell and the products to be produced therein. A crucial aspect of this RQ is to incorporate the flexibility as identified in the previous RQ into the design. Where the current methodologies and approaches for designing work cells and products incorporate flexibility, it is though either to a limited degree or without the perspective of the flexibility types that a MMS enable. Additionally, as the flexibility increases, the design complexity increases, thus a more thorough attention to this aspect is needed to optimize the flexibility and performance of the manufacturing system.

The third RQ refines this flexibility and performance optimization by focussing on the control of MMS. The control phase of a MMS is crucial as it orchestrates the flexibility types that the manufacturing system facilitates. Additionally, the control system for a manufacturing system and the design form a symbiotic relationship hence a more flexible design requires a more flexible control system. Similar to the design phase, the current literature on control systems for manufacturing systems does not fully enable the potential of MMS. In this way, MMS are investigated from the design to the control phase, thus addressing how to operationalize this type of manufacturing system and its flexibility.

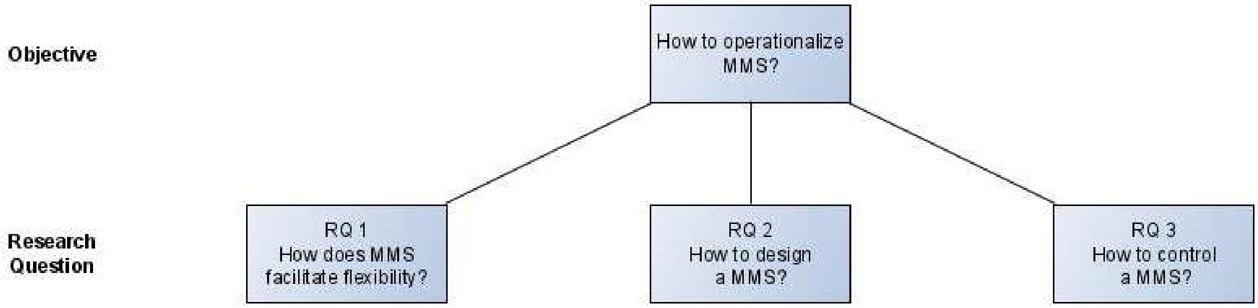

Figure 1 Overview of RO and RQs

1.4 Structure of the Dissertation

The kappa of this paper-based PhD dissertation is divided in six sections, where the following section presents and analyses the current literature, serving as a foundation for the remaining sections. The third section presents the research design, including the different research methodologies applied. The fourth section presents the results related to the research questions. The fifth section discusses the findings in the kappa in relation to supply chains, sustainability, and new business opportunities, while the last section concludes the dissertation and presents future works. Appended to the kappa, the four fundamental publications can be found, together with co-author statements. The structure of the dissertation is illustrated in Figure 2.

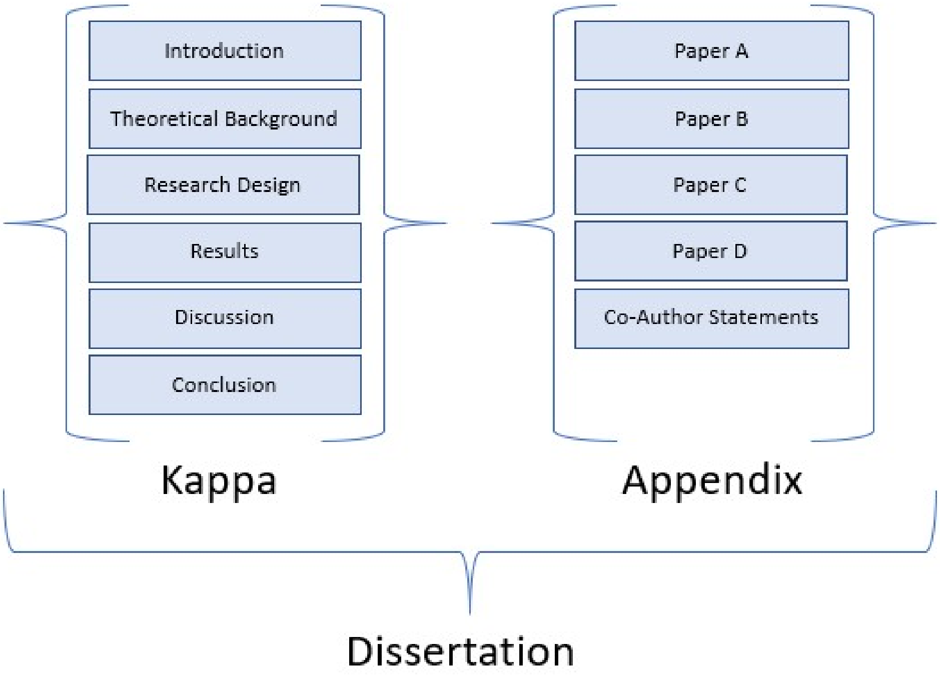

Figure 2 Structure of dissertation

2. Theoretical Background

In this section, the background from the introduction of the PhD kappa, is expanded in three key areas; Flexibility in manufacturing systems, MMS, and DT. In the first subsection, flexibility is defined and presented in relation to different manufacturing system paradigms. Afterwards, MMS are presented together with the current literature on the topic. As a continuation of this, DT, a crucial tool in this dissertation, is explored, and the state-of-the-art is presented.

2.1 Flexibility in Manufacturing Systems

Manufacturing systems have, since the first industrial revolution, experienced the emergence of different paradigms. These paradigms have been introduced due to various factors, but especially the production volume and product variety aspects have been crucial for new paradigms to develop (ElMaraghy *et al.*, 2013). As illustrated in Figure 3, various manufacturing paradigms exist that balance these two aspects. It is though clear from the figure that a higher productivity implies a lower flexibility and vice versa. Recently, the need for more flexibility has increased together with the need for a higher production volume. This transition from High Mix Low Volume (HMLV) and Low Mix High Volume (LMHV) productions to High Mix High Volume (HMHV) productions require a new paradigm in the manufacturing system domain. It is though crucial to first investigate the different types of flexibility, in order to more sufficiently classify and compare the manufacturing system paradigms from Figure 3.

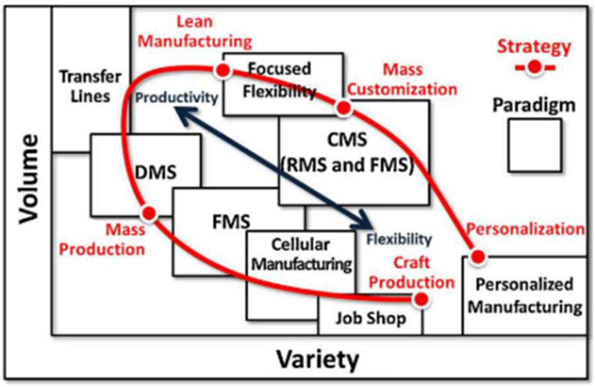

Figure 3 Relation between production volume and variety for manufacturing system paradigms, adapted from (ElMaraghy et al., 2013).

ElMaraghy summarizes 10 types of manufacturing system flexibility, as seen below. These types of flexibility are crucial for understanding the levels of flexibility, a manufacturing system can posses, as well as for the decision-maker to correctly identify the ideal paradigm when designing a production. These 10 types of flexibility will furthermore be used as a measurement based on a categorical indicator for comparison between the different following manufacturing paradigms.

The 10 types of flexibility are according to ElMaraghy: “

1. Machine flexibility: Various operations performed without set-up change,
2. Material handling flexibility: Number of used paths / total number of possible paths between all machines,
3. Operation Flexibility: Number of different processing plans available for part fabrication,
4. Process Flexibility: Set of part types that can be produced without major set-up changes, i.e. part-mix flexibility,
5. Product Flexibility: Ease (time and cost) of introducing products into an existing product mix. It contributes to agility,
6. Routing Flexibility: Number of feasible routes of all part types/Number of part types,
7. Volume Flexibility: The ability to vary production volume profitably within production capacity,

8. Expansion Flexibility: Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system,
9. Control Program Flexibility: The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software,
10. Production Flexibility: Number of all part types that can be produced without adding major capital equipment." (ElMaraghy, 2005)

These types of flexibility are strongly connected to the different paradigms, presented in Figure 3. The paradigms do though integrate the different types of flexibility at different levels. It is therefore crucial to have a solid knowledge of each paradigm to provide a foundation for comparing the different paradigms to MMS. This foundation can be found in Table 1 on page 20 that relates the 10 types of flexibility and their level to each paradigm. The paradigms selected for this analysis are described below.

Cellular Manufacturing Systems, a manufacturing application of Group Technology from the 1970s, describes the processing of part families in grouped machines, cells, or similar (Singh, 1993). One of the key challenges with this type of manufacturing system is the formation of these cells. Typically, machines are physically grouped together, which on the one hand, optimizes the performance of the cell producing that specific part family, but on the other hand, requires a significant initial investment. Furthermore, the sharing of machines between cells is not considered, often resulting in a low Overall Equipment Efficiency (OEE). One approach within Cellular Manufacturing Systems that address this challenge is the Virtual Cellular Manufacturing Systems that in this way introduces a flexible routing between the machines in the cells (Nomden and van der Zee, 2008). This furthermore adds demand flexibility, corresponding to product and volume flexibility (Askin, Selim and Vakharia, 1997). The types of flexibility that Cellular Manufacturing Systems provide is summarized in Table 1.

FMS is a paradigm that has been around for several decades. While there is no single, generally accepted definition (Kaighobadi and Venkatesh, 1994), ElMaraghy defines it as follows "A Flexible Manufacturing System is an integrated system of machine modules and material handling equipment under computer control for the automatic random processing of palletized parts." (ElMaraghy, 2005). This definition implies different types of flexibility, as seen in Table 1. Furthermore, Kulatilaka describes how a FMS enables both a flexible capacity, product flexibility, and process flexibility (Kulatilaka, 1988). Similarly, Chan addresses the routing flexibility in a FMS (Chan, 2010), although the results yield that the routing flexibility does not play a crucial role in the experiment presented in the paper.

FFMS were initially proposed to address the challenges of the broad concept of flexibility that often adds unnecessary pressure on the system design (Fogliazza, 2004) or, as proposed by Tolio and Valente, to minimize the level of flexibility, thus focusing it on the necessary processes (Tolio and Valente, 2006). FMS, by nature, for example, implements a high degree of product flexibility, typically as a consequence of the machine selection. This adds additional costs to the system design that might imply challenges in a cost-sensitive manufacturing setup. FFMS address this challenge by focusing on the level of flexibility based on the production requirements, thus precisely balancing the productivity and flexibility in a given manufacturing environment (Terkaj, Tolio and Valente, 2009). This implies that FFMS can combine flexible machining centers and dedicated machining centers, thus tailoring the productivity and flexibility to the requirements of the manufacturing system (Terkaj, Tolio and Valente, 2010).

RMS are a paradigm that has gained popularity in the last decades. Various definitions exist, also in relation to how it differs from for example FMS (Bi *et al.*, 2008), however this kappa adapts the definition by Koren et al. as “A Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.” (Koren *et al.*, 1999). Hence, the flexibility degree is enabled through modularity in both hardware and software, as well as convertibility on system, component, and software level. This reconfigurability on the machine tool level, also known as Reconfigurable Machine Tools (RMT), is a major component of the overall manufacturing system (Landers, Min and Koren, 2001). These machine tools, in comparison to general-purpose Computer Numerical Control (CNC) machines, are designed with the part family in focus, thus the flexibility is more customized, in contrast to the more general flexibility that CNC machines enable. The RMT does in this way facilitate product flexibility, as the time and cost of introducing a new product solely requires an adoption of a machine tool, rather than – in a FMS worst case scenario – a new machine.

CMS encompass both aspects of FMS and RMS to enable changeability. Wiendahl et al summarize Tolio commenting that even though in specific instances, reconfigurability and flexibility can be distinguished, the terms cannot generally be described sufficiently. Hence, it is suggested that in general statements to use “changeability” as it includes both reconfigurability and flexibility (Wiendahl *et al.*, 2007). In the paper by Wiendahl et al., the authors further focus on the flexibility aspect of changeability, stating “Changeability in this context is defined as characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically.” (Wiendahl *et al.*, 2007). According to ElMaraghy, the CIRP academic and industrial community has adopted the following Figure 4 to classify changeability and how it relates to RMS and FMS (ElMaraghy, 2005). Similarly, Andersen et al describe changeability as a combination of flexibility and reconfigurability, and investigate the critical enablers in a empirical survey (Andersen *et al.*, 2018).

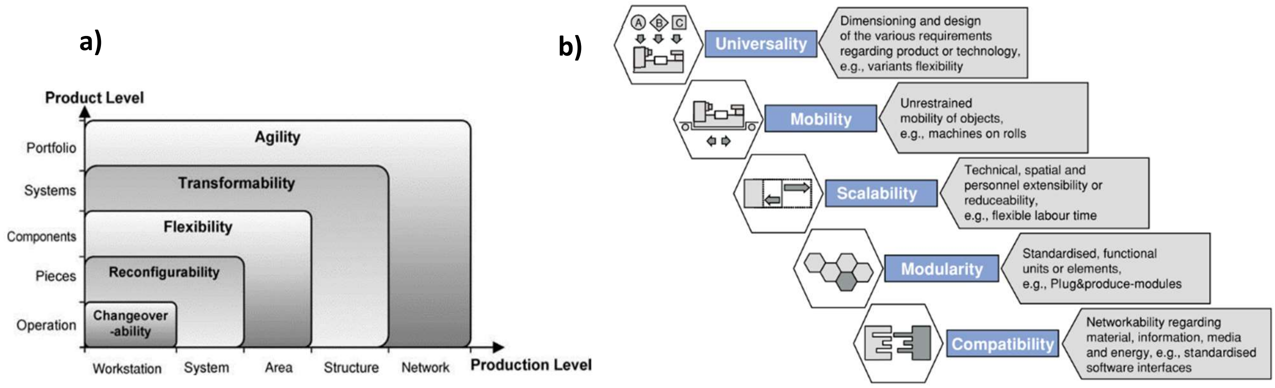

Figure 4 Aspects of CMS: a) relating product and production level in relation to changeability, b) describing changeability aspects

The concept of “Matrix Production”, was initially coined by Greschke et al. in 2014. In this paper, Matrix Production is defined as a manufacturing system consisting of multiple standardized, reconfigurable work cells with a flexible material between each work cell (Greschke *et al.*, 2014). Typically, these work cells are structured in a matrix, as seen in Figure 5, and depending on the tools they are equipped with, they can perform various processes. This is indicated in the figure by the different numbers in the blue circles, representing a different process that the work cell is capable of performing. A further description of this manufacturing system and the different kinds of flexibility can be seen in section 2.2.

	Cellular	**Flexible**	**Focused Flexibility**	**Reconfigurable**	**Changeable**	**Matrix-Structured**
Machine	◑	●	●	◑	◑	◑
Material Handling	◔	◑	◑	◑	◑	●
Operation	◔	◔	◔	◑	●	●
Process	◔	●	◑	●	●	●
Product	◑	●	◑	●	◑	●
Routing	◑	◑	◑	◑	◑	●
Volume	◑	●	◑	●	●	●
Expansion	◔	◔	●	●	●	●
Control Program	◔	◑	◑	●	●	◑
Production	◔	●	◑	●	●	●

Note: ○ *= Low degree,* ● *= High degree*

Table 1 Type of Flexibility for various manufacturing systems

From Table 1, it is clear that MMS differs from the current manufacturing system paradigms not only through the types of flexibility that it enables but also due to the level of flexibility. The types of flexibility are either enabled through the design and nature of the paradigm as well as the technologies applied. To provide the solid theoretical background for answering the RQs, it is though crucial to further investigate MMS and the different perspectives the current literature has on the manufacturing system.

Please note that Table 1 has been filled out through a brief qualitative investigation of the academic literature and reflection thereof, and thus represents unpublished, non-peer reviewed work. As the scope of the kappa is solely focused on MMS, this is further investigated, while the remaining manufacturing systems and the flexibility levels are subject to future research. It is important to highlight that the future research will improve on partially methodology, such as multiple systematic literature reviews, as well as form and template.

2.2 Matrix-Structured Manufacturing Systems

The term, Matrix-Structured Manufacturing Systems, was proposed by Schönemann et al. (Schönemann *et al.*, 2015) and shares many of the same similarities as "Matrix Production" proposed by Greschke et al. (Greschke *et al.*, 2014). Before further expansion on the definition of MMS from "Dissertation" on page 3, it is though important to first of all understand the intention of MMS. The intention of MMS is to efficiently balance a production with a certain variance in the cycle times, especially when producing products from one or more product portfolios with varying product demand. Thus essentially, MMS intends to provide a dynamically optimized solution for throughput of the manufacturing system to the three "degrees of freedom"; cycle time, product variant, and product variant demand.

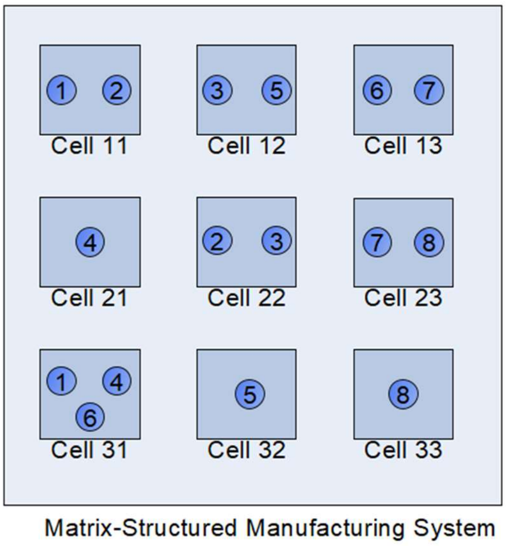

Figure 5 Example of a MMS setup, adapted from (Nielsen, da Silva and Yu, 2020)

With a clear intention of the manufacturing system, an expansion of the initial definition from page 3 creates a more thorough understanding of the concept. The following expansion of the definition partly exemplifies the aspects from the initial definition, and partly provides a detailed insight into the technicalities of the manufacturing system. Recalling the initial definition, as summarized below, it can be divided into four distinctive aspects; The work cells, the topology, the intralogistics, and the dynamic behavior.

A manufacturing system consisting of flexible and reconfigurable, standardized work cells, typically structured with a matrix-like topology. The intralogistic transportation between the work cells is realized through flexible means of transportation. The manufacturing system is dynamically adaptable to internal and external conditions.

The work cells, described as subsystems by Grescke et al (Greschke *et al.*, 2014), provide the backbone of the manufacturing system paradigm. The work cells typically consists of two major components; a buffer and the value-adding work stations (Schönemann *et al.*, 2015). The buffer serves the purpose of temporary storage that, due to the variance in cycle times and transportation time practically creating small blocking and waiting times, easily can increase efficiency of the manufacturing system. The work stations are however the value-adding elements in the work cells, as they are actively processing the products. The work stations are fundamentally designed to be standardized, flexible and reconfigurable (Nielsen and Yu, 2022). Breaking down these three parameters, the work stations are essentially; the same that is duplicated in the layout, capable of producing different product variants, and augmentable by changing the manufacturing tools and equipment. Thus, it can be summarized that through the reconfigurable capabilities, the work cell can – theoretically – perform all possible processes to produce all product variants that the manufacturing system is designed to produce. As the work cells are standardized, the equipment can furthermore be shared among work cells to dynamically augment the local capabilities in the system. Practically, this does though require that the work cells and product portfolios are symbioticly designed (Nielsen and Yu, 2022). To briefly discuss a crucial aspect, Greschke et al and Schönemann et al argue that a buffer is a basic element of a MMS (Greschke *et al.*, 2014; Schönemann *et al.*, 2015), it can however be argued that under certain conditions, it is unnecessary. For example, a just-in-time production with a sufficient amount of work cells would due to the dynamic behavior and reconfigurability capabilities – theoretically – not strictly need a buffer. However, for redundancy and practical implementations, the buffer is typically added, as the theoretical constraints of the manufacturing system is not directly transferrable to the practical constraints.

The second aspect of MMS is the topology or layout of the manufacturing system. As the manufacturing system does not follow a linear, fixed material flow through the work cells, such as traditional manufacturing systems, the crucial part of the topology is to minimize the intralogistics transportation of products and tools between the work cells. This is typically realized when the work cells are located in parallel to each other, efficiently creating routing paths on all sides of the work cells (Greschke *et al.*, 2014), as can be deduced from for example Figure 5. As the intralogistics transportation can be performed both horizontally and vertically and of any distance, the topology combined with the flexible intralogistics transportation enables the opportunity to distribute products based on the actual work cell configurations, as well as work cell state, such as failed, operational, blocked, waiting, recovering, etc. It is though important to highlight that the layout does not strictly have to be in a matrix setup to enable the benefits of this manufacturing system paradigm, however for practical reasons, this is the typical implementation.

The third aspect of MMS is the intralogistics transportation. It is typically carried out with AGVs or AMRs (Fries, Wiendahl and Assadi, 2020), allowing dynamic routing, for example, in case of unexpected work cell failure. It is however important to highlight that it – theoretically – is not strictly necessary to utilize this form for transportation. Under certain conditions, cranes can for example be a more suitable solution, all depending on the products that the manufacturing system should be capable of producing. The key purpose of the intralogistics is though the flexibility to potentially transport the products to all work cells. Due to the topology of the manufacturing system

If a work cell failure occurs, other work cells can easily be reconfigured to perform these processes, thus ensuring redundancy. In addition to this, it is also possible to quickly scale up and down the production volumes of specific variants or even product families, as presented in the case study by (Nielsen, da Silva and Yu, 2020). The possibility of efficiently and simultaneously producing multiple product families is further enabled by the takt-time independence between each work cell. In this way, more process-intensive products do not influence the production of less process-intensive products, as they will be manufactured in other work cells.

As identified by Schönemann et al. a high overall utilization is directly linked to as high a utilization of each work cell as possible (Schönemann *et al.*, 2015). However, little efforts within this area have been made in litterature to address this crucial point in MMS. Paper B and Paper C does though address this research gap, by respectively focusing on the work cell design and product family design targeted MMS. This topic will be further expanded in section 4.2. It is though crucial to highlight that the nature of the work cells enable not only product flexibility, but also process flexibility and to some extent machine flexibility. As the work cell design and product family design form a symbiotic relationship, it is necessary to also address the products to be produced.

As MMS enables the production of multiple product families in parallel, reconfiguration of the work cells are a central part to ensure the right tools and fixtures are installed in the work cells. Ideally, this reconfiguration is fully automated, where the tools and fixtures are transported from a tool store by the AGVs or AMRs. This tool store can, depending on the frequency of reconfiguration, either be implemented directly into the work cells, or be centralized in a local tool store. This furthermore allows tool sharing between the work cells that yields several benefits. First of all, the redundancy is increased in case a work cell component is failing, the tool can be detached and installed in a functional work cell, while the failing work cell is under repair. Furthermore, the overall tooling cost is minimized, as the amount of tools needed solely are connected with the production volume projections. This also influence the volume flexibility, as more tools eventually can be acquired in case upscaling is needed. Finally, the introduction of new products or product families are solely dependent on the development of new low-cost tools and the Bill of Processes (BoP) rather than introducing new machines. In other words, this increases the product and operation flexibility.

A crucial aspect of the flexible material flow, is the AGV or AMR control, where different control algorithms have been applied (Li *et al.*, 2021; Zhang *et al.*, 2022). Similarly, Bányai presents flower pollination and black hole heuristic-based algorithms to address the optimization of material supply (Bányai, 2021). As the material flow is inevitably a strength of the manufacturing system, it also introduces potential inefficiency, especially in an unoptimized state. These recent works therefore highlights the importance of an optimized material flow in a MMS.

Multiple simulation studies have been carried out in connection with the conceptual development of MMS (Schönemann *et al.*, 2015; Filz *et al.*, 2019; Schumacher, Weckenborg and Spengler, 2021). Discrete Event Simulation (DES) has for example been applied in a wide variety of application areas, ranging from increasing resilience (Ihlenfeldt, Wunderlich, Süße, *et al.*, 2021) to Artificial Intelligence (AI) (Minguillon and Lanza, 2019). Simulation as a methodology is a crucial aspect for the development of MMS, as it enables a risk-free exploration and evaluation of possible solutions. However the challenge has often been converting the digitalized model to a physical representation. While the idea of letting the simulation environment control the physical environment is not new (Bilberg and Alting, 1991), recent developments within the Digital Twin field has shown promising results. This topic is further explored in the following section.

2.3 Digital Twins in MMS

The term, DT, was initially coined in the beginning of the Millenium by Michael Grieves (Batty, 2018), although the “twin concept” is based on the Apollo program by the American National Aeronautics and Space Administration (NASA). Here two identical space vehicles were produced, where one of these space vehicles were then sent to space, while the other were stationary on Earth. In this way, it would be possible for the Earth-based experts to mirror the conditions experienced on the space-bound vehicle and simulate possible solutions to challenges (Boschert and Rosen, 2016).

DT have in recent years gained in popularity, yielding a multitude of various definitions (Grieves and Vickers, 2017; Negri, Fumagalli and Macchi, 2017; Haag and Anderl, 2018; Tao *et al.*, 2018). While these definitions share many similarities, they also have slight variations. Based on these definitions, a DT in this kappa is regarded as a digital representation connected through bi-directional communication with a physical representation, as illustrated in Figure 6. It is important to clarify that bi-directional communication not necessarily has to be balanced in terms of quantity sent and received, but solely the presence is the enabler. Furthermore, bi-directional communication can be temporarily disabled to allow for experimentation in the physical or digital representation. In this way, optimizations achieved in the digital representation, typically implemented as a simulation model, can be pushed to the physical representation and vice versa. This is further elaborated on in the book chapter by da Silva, Neto, and Nielsen (Ribeiro da Silva, Assad Neto and Nielsen, 2023).

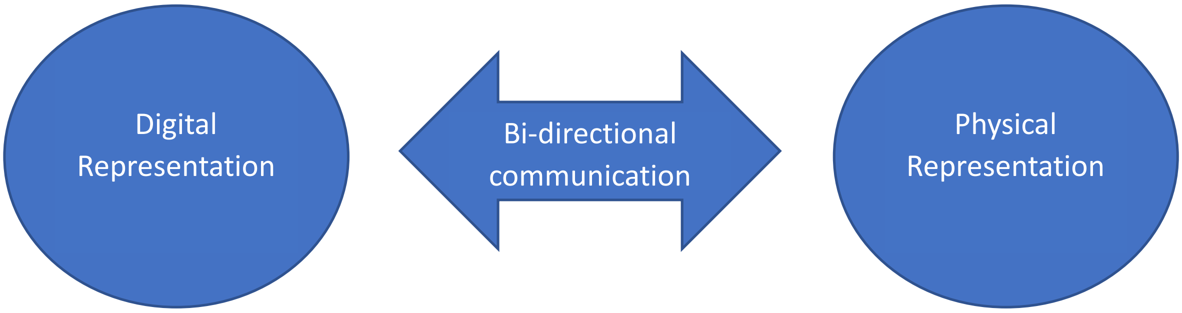

Figure 6 Digital Twin concept

To extend on the definition of a DT, Jones et al. has identified 13 characteristics that characterize a DT in their systematic literature review. These characteristics are 1) physical entity, 2) virtual entity, 3) physical environment, 4) virtual environment, 5) state, 6) realization, 7) metrology, 8) twinning, 9) twinning rate, 10) physical-to-virtual connection, 11) virtual-to-physical connection, 12) physical processes, and 13) virtual processes (Jones *et al.*, 2020). These 13 characteristics will form the basis for the remaining section on the theoretical background of DT to describe the concept in more detail.

The physical entity, also known as the physical twin or physical representation, describes the real-world existing system, product, part, supply chain or otherwise tangible asset for the domain-specific topic (Jones *et al.*, 2020). In the manufacturing domain, the physical entities are represented by the equipment on the shopfloor, for example a Computerized Numerically Controlled machine (Cai *et al.*, 2017), a cutting tool for this type of machine (Botkina *et al.*, 2018), work cell as proposed in Paper B, or even the full manufacturing line (Zhang *et al.*, 2017). The virtual entity, also known as the virtual twin, or digital representation, describes the digital equivalent to the physical entity. Similarly, this entity is also referred to differently, depending the domain-specific area (Jones *et al.*, 2020).

The physical environment describes the real-world, tangible, and measureable environment in which the physical entity exists (Jones *et al.*, 2020). The physical environment in the manufacturing domain is generally considered potentially fully observable within the physical barriers defined by the purpose of the DT. The virtual environment is however typically developed in a simulation environment and with a specific purpose in mind, although intended to sufficiently correspond to the physical environment (Ribeiro da Silva, Assad Neto and Nielsen, 2023). This purpose of the virtual environment can for example be decision-support for order management processes (Kunath and Winkler, 2018). It is though important to take into account that the virtual environment often is a simplification of reality, and the famous words by statistician George E.P. Box “All models are wrong, but some are useful” (Curchoe, 2020) applies in this case. This is primarily due to the limitations of the (simulation) software used to model virtual environment.

The state represents measurements for all parameters of the virtual entity, the physical entity, or their respective environments. These states are typically customized to partially what is measurable in the physical environment, as well as what is possible to represent in the virtual environment. An example thereof could be a machine state following PackML (Um, Weyer and Quint, 2017).

For the realization and metrology, these are described as respectively the act of changing the physical or virtual entity, and the act of measuring these entities (Jones *et al.*, 2020). This is naturally connected with the input and output parameters that the virtual entity can posess, as well as the sensors and actuators on the physical entity. The metrology characteristic is for example applied in DT of cutting tools to ensure that the physical entity corresponds to the virtual entity (Botkina *et al.*, 2018).

The twinning and twinning rate characteristics are important aspects of the DT. They describe the act of synchronizing the physical and virtual entities, as well as the frequency they are synchronized. The twinning process therefore consists of both metrology and realization when a change in either the virtual or physical entity occurs (or at a given twinning rate) (Jones *et al.*, 2020).

In the physical-to-virtual and virtual-to-physical connection, the processes or data connections are described of the twinning. This can also be described as what the bi-directional communication, illustrated in Figure 6, performs. Essentially, these processes encompass both the metrology, realization, twinning, and twinning rate characteristics and therefore describes how the twinning is performed (Jones *et al.*, 2020).

Finally, the virtual and physical processes describe the actions performed in the virtual or physical environment by their entities. For the physical processes, this can for example by subtractive manufacturing (Botkina *et al.*, 2018), or manufacturing (Zhang *et al.*, 2017), while the virtual processes for these two examples respectively are improvements of process understanding to better predict behavior, and optimization.

When designing a DT, Madni, Madni and Lucero define four levels of digital twins; (1) Pre-Digital Twin, (2) Digital Twin, (3) Adaptive Digital Twin, and (4) Intelligent Digital Twin (Madni, Madni and Lucero, 2019). The first level describes a virtual prototype comparable to a simulation model. This allows the developer of the DT to experiment and explore possible solutions in a risk-free environment. The second level describes the digital twin, with a physical representation and a bidirectional communication between. Here, the physical representation is used to verify and validate assumptions from the digital representation by exposing the physical representation to a controlled environment. The third level describes an adaptive digital twin that adopts AI in the form of supervised ML. This ML is targeted towards learning the preferences and priorities of human operators, primarily through the interaction with the user interface. The fourth level intelligently applies ML aspects to the system and environment, thus optimizes itself over time.

As identified by Madni, Madni and Lucero, it is crucial to apply the pre-digital twin, typically implemented as a simulation model, to mitigate the technological risks that might appear (Madni, Madni and Lucero, 2019). This implies that selecting the appropriate simulation tool(s), thus the foundation for the DT, is of highest importance. While several criteria have been identified (Hlupic and Paul, 1999; Jadhav and Sonar, 2011; Constantinescu *et al.*, 2014) and various methodologies for software selection has been suggested (Saaty, 1990; Jadhav and Sonar, 2009), as summarized in the paper by Yu and Nielsen (Yu and Nielsen, 2020). It is though also crucial to ensure that the simulation solutions sufficiently can integrate with the bi-directional communication as well as precisely mirror the physical system for the given task.

DT play a central role in the development of MMS. Although current literature connecting DT and MMS is strictly limited (Nielsen, da Silva and Yu, 2020), simulations play a crucial role, as identified in section 2.2. These pre-DT allow on a manufacturing system level, for example, to analyze different material supply strategies (Filz *et al.*, 2019). On the work cell level, a DT is applied to verify and validate the performance of the work cell prototype prior to deployment, as described in Paper B and Paper C. Finally, in Paper A, the real-time updated simulation model is used as a foundation for training an AI agent, thus reaching a level four, intelligent DT as proposed by Madni, Madni, and Lucero (Madni, Madni and Lucero, 2019).

3. Research Methodology

This section describes the research design of the PhD, and how the research methods have been applied to generate the results that answer the research questions. This is furthermore illustrated in Figure 7, providing an overview thereof. The two primary methodologies applied throughout the PhD study are the systematic literature review and case study. Simulation and DT are though fundamental tools applied in the case studies.

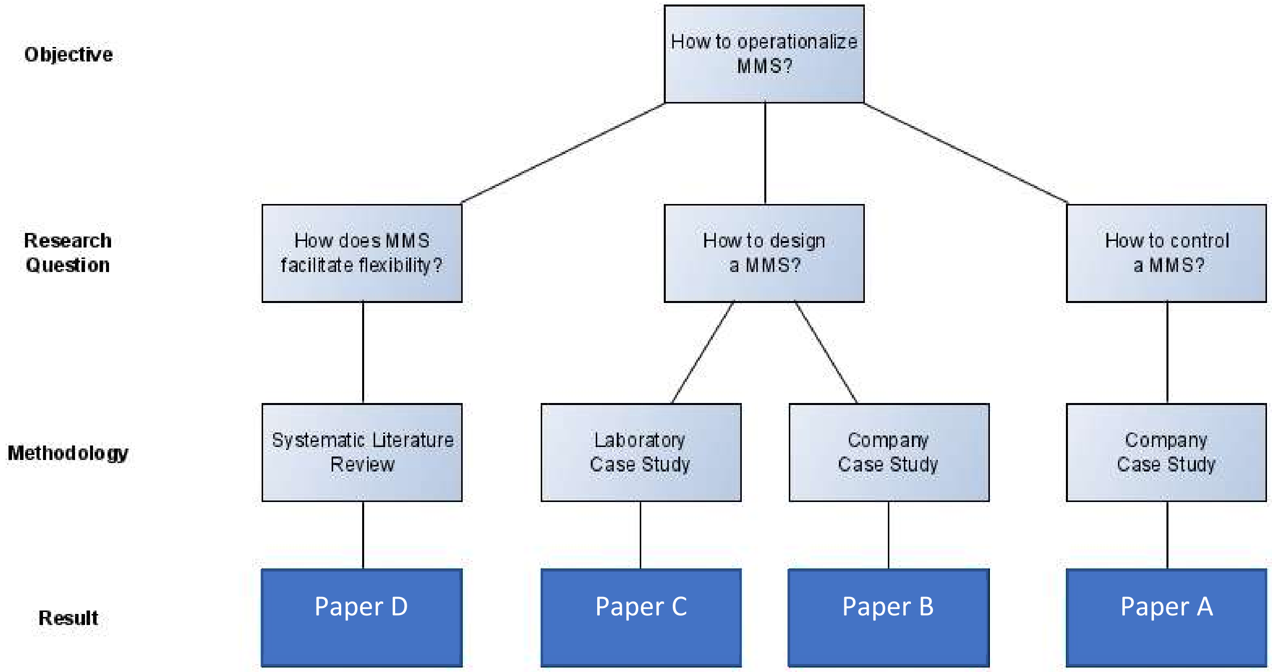

Figure 7 Overview of RO, RQs, methodologies and results

3.1 Research Design

The strategy to select the appropriate methodological approach for the RQs consists of several considerations that all ensures a thorough, sufficient, and elaborated investigation of the overall. This means that not only are the methodological approaches to answer each RQ investigated separately, but also with the combination of the selected methodological approaches in mind. Based on this foundation, it is therefore necessary to consider the type of research. In engineering research, Deb, Dey, and Balas describe types of research to be either; 1) Descriptive or Analytical, 2) Applied or Fundamental, and 3) Quantitative or Qualitative (Deb, Dey and Balas, 2019, p. 5). These aspects have been crucial for the research design and selection of methods for the RQs and to provide an also varied methodological approach.

For the first RQ, “How does MMS facilitate flexibility?”, the three types of research, as described by (Deb, Dey and Balas, 2019, p. 5), have been evaluated. First, it is analyzed whether a descriptive or analytical approach would be suitable to address the RQ. A solely descriptive approach, with the purpose of objectively identifying the flexibility characteristics of a MMS, would initially be a suitable approach to expand the current knowledge. To sufficiently identify the full characteristics, this approach requires a relatively large amount of academic literature as a solid foundation to effectively describe the state-of-the-art. Given the relatively recent academic introduction of Matrix Production in 2014 (Greschke *et al.*, 2014) leading to MMS in 2015 (Schönemann *et al.*, 2015), it was early deemed that a solely descriptive approach would not be sufficient to fully answer the RQ. Additionally, the nature of the RQ also requires an analytical consideration, where a critically assessment of partially literature but ideally also industrial or academic implementations is necessary. The critical assessment is important in this regard, especially considering actual implementations, as they naturally rely on for example physical constraints, compromises connected to limited resources, and subjective bias. Therefore, descriptive elements are needed, although to sufficiently answer this research question, an analytical approach will be taken based on the descriptive outcome.

The second type of research by (Deb, Dey and Balas, 2019, p. 5), focus on the applied or fundamental research. The purpose of the RQ is to partly provide a foundation for applied research, as well as providing a generally applicable outcome that highlights the flexibility types of MMS and how they are facilitated. While the nature of the RQ does not invite for an applied approach, primarily due to the lack of a practical problem to be solved, it is therefore deemed to follow a fundamental research approach. The third type of research by (Deb, Dey and Balas, 2019, p. 5), focus on the qualitative or quantitative approach. Taking the RQ and two previous types of research into account, a quantitative approach with a sufficiently large data pool would be ideal, however due to the limited number of academic publications on MMS, and especially on MMS and flexibilility, a qualitative approach is the only applicable option at the time of writing. Thus to conclude on the research types, to address RQ1, analytical, fundamental and qualitative approaches will be applied to provide an answer to the research question. Based on these approaches, it is crucial to identify and apply a sufficient methodology. Given the fundamental approach in combination with the clear lack of a multitude of potential MMS to physically visit, academic literature was determined to provide the primary data source to analyze. While it indeed would be beneficial to observe multiple actual implementations of MMS with the intend to objectively describe different types of flexibility in these systems (although this points in the direction of a descriptive research approach), this dataset would also include larger degrees of subjectivity, adaption to manufacturing needs and demands, and thus a strong bias. While bias is indeed inevitable, academic literature tends to have a more theoretical perspective, and thus the degree of bias is less. Based on this, a systematic literature review was selected as the methodology. While this methodology can be regarded as a quantitative approach (Snyder, 2019), Snyder also highlights that a systematic literature review process can be applied to identify and select the academic records, followed by a more qualitative approach to assess them (Snyder, 2019). It is though fundamental to have an analytical approach towards the quantitatively sourced literature to end up with a qualitative and generally applicable answer to the RQ. The systematic literature review process is described in section 3.2.

The second RQ, “How to design a MMS?”, is also analyzed based on the three types of research by (Deb, Dey and Balas, 2019, p. 5), taking the research types and methodology of the first RQ into account. First, it is considered if an applied or fundamental approach is to be selected. A fundamental approach would indeed be desirable for this RQ, as the outcome would be more generally applicable. An applied approach would here focus on a specific problem in an organization. While the intention of the RQ is to provide a more generally applicable answer, the opportunity of performing applied research in a company is also present. While there are risks for bias, when attempting to generalize the outcome of an applied approach, it was determined to address this RQ through an applied approach. Secondly, it was analyzed whether a qualitative or quantitative approach should be selected. While the quantitative approach in this case would be ideal, the strictly limited number of industrial and academic cases to analyze leaves little opportunity for this approach. The quantitative approach would indeed, as described earlier in this section, introduce a strong bias due to the compromises taken when designing, implementing, and commissioning manufacturing systems. While there is also a strong bias in a qualitative approach, especially due to the limited number of observations, it also pose the challenge of ensuring that the selected data source is representable, and thus that the results are valid. The validity of qualitative research has been addressed in literature, where Morse et al. present different verification strategies to ensure that the qualitative research is valid (Morse *et al.*, 2002). Based on this foundation, the qualitative approach was deemed appropriate to address this RQ. Finally, it was analyzed whether a descriptive or analytical approach should be selected for the second RQ. Where a descriptive approach would solely allow to report the variables identified throughout the research as-is, this would not cohere with the applied approach previously selected for this RQ. An analytical approach is therefore to be selected, also due to the critical approach for analyzing the outcome. This is especially beneficial in connection with the qualitatitive approach, where a limited number of cases to investigate is available. It can therefore be concluded that the second RQ follows an analytical, applied and qualitative approach. On this foundation, the methodology to analyze the RQ with these research types in mind, is to be selected. Given the applied, qualitative and analytical approach, case studies were selected. Initially, only a laboratory case study was proposed, primarily due the verification strategy of a more methodological coherence, as described by (Morse *et al.*, 2002). By performing the case study in a laboratory, there is on the one hand a more direct control over the variables in the study, however on the other hand, this also introduces much more bias. As the opportunity for a company case study emerged, it was evaluated whether the applied, qualitative, and analytical approach would still be applicable, and in this case with a positive evaluation. However, this on the one hand strengthens the academic contribution, it on the other hand also introduces higher degrees of bias, resulting in more efforts on the verification strategies in the qualitative research. Especially, the theory development as a verification strategy, as described by (Morse *et al.*, 2002), yielded significantly more efforts to ensure applicable results, due to the bias that was performed when developing the MMS in the case company. However, the combination of a laboratory case study with a company case study allowed an approach to balancing the control of important variables, and thus complementing each other in regards to minimizing bias. The company and laboratory case studies related to the second RQ is described in section 3.3.

For the third RQ, “How to control a MMS?”, the same analysis was performed as with the previous two RQs. Without taking the outcome of the two previous RQs into account, a descriptive approach of manufacturing control systems could be applied, due to the comparative methods between MMS and other manufacturing systems. Following the descriptive approach, with academic literature as the primary datasource, the answer to the RQ would be of a more theoretical character, especially if combined with a fundamental and quantitative approach. While these approaches would provide a broader coverage of different research types with a more elaborated methodology, it would however also present challenges on verifying the practical aspects on the overall RO. Therefore, taking the research types and outcome of the two previous RQs into account, it was determined that an applied approach with an analytical and qualitative aspect would sufficiently address this RQ. The analytical approach has been selected as a clear outcome of the two previous RQs indicated that the current approaches to control systems does not suffice to efficiently leverage the multitude of flexibility types that MMS facilitates.

3.2 Systematic Literature Review

When performing literature research, a multitude of different methodologies can be selected to provide the necessary knowledge. These methodologies, as provided in the overview by Snyder (Snyder, 2019), are summarized below.

- Systematic literature review (SLR)
- Semi-systematic literature review
- Integrative literature review

It is though crucial to highlight that despite the shared goal of the literature reviews – to present the state-of-the-art research – the different methodologies vary in terms of their focus and outcome. The SLR collects all research records within the specific search criteria, compared to the semi-systematic literature review that only collects relevant articles, typically due to the size of the research area and the number of publications. The integrative review differs slightly in terms of purpose, as it aims to provide a new (critical) view of a given, established research area.

To address RQ1 in this kappa, the SLR has been selected due to its thorough approach, transparency, and reproducibility. Furthermore, the research area is relatively new, indicating that it will not be possible to apply the benefits of a semi-structured or integrative literature review. Finally, it is generally accepted "as the gold standard among reviewers" (Snyder, 2019), due to the beforementioned benefits. Within the SLR methodology, the PRISMA 2020 statement has been selected to ensure a consistent replicable approach to the SLR (Page *et al.*, 2021).

The PRISMA statement was initially applied in the medical field for evidence-based literature reviews, ensuring transparency and reproducibility. However, it has gained popularity in other research areas for the same reasons. The updated PRISMA 2020 statement includes a 27 item checklist and a flow diagram template as presented in the paper by Page et al. (Page *et al.*, 2021). This SLR will focus on the flow diagram with the items as the foundation.

The key purpose of this literature review is to identify the current literature on MMS with focus on flexibility and how MMS facilitates it. The literature will then serve as the basis for this PhD kappa and the remaining RQs. By grouping the literature on MMS, it will furthermore be possible to highlight the current focus areas, indicating the direction of the research. Therefore, the question this literature research answers is: *How does Matrix-Structured Manufacturing Systems facilitate flexibility*?

Prior to the SLR, a smaller preliminary literature review has been performed to gain the necessary knowledge of the field. This, for example, includes what is considered the first defining publication on the concept of matrix production by Greschke et al. (Greschke *et al.*, 2014). The information from this preliminary literature review has been applied to determine the boundary conditions for the SLR, specifically in regards to the publication year. This has served as a search refinement parameter, as indicated in Table 2.

For the SLR, four databases have been selected, as indicated in Table 2. These databases are selected based on their broad coverage and general acceptance within the research area of manufacturing. As indicated in the paper by Singh et al. (Singh *et al.*, 2021), Scopus and Web of Science consist respectively of 20.6% and 24.4% of publications targeting the technological fields. Furthermore, these databases covers a multitude of relevant countries performing research within the manufacturing domain, as seen in Figure 8. IEEE Explore and Sciencedirect has been selected due to similar reflections, where Dimensions, as mentioned in the paper by Singh et al., was not available at the time of the literature research.

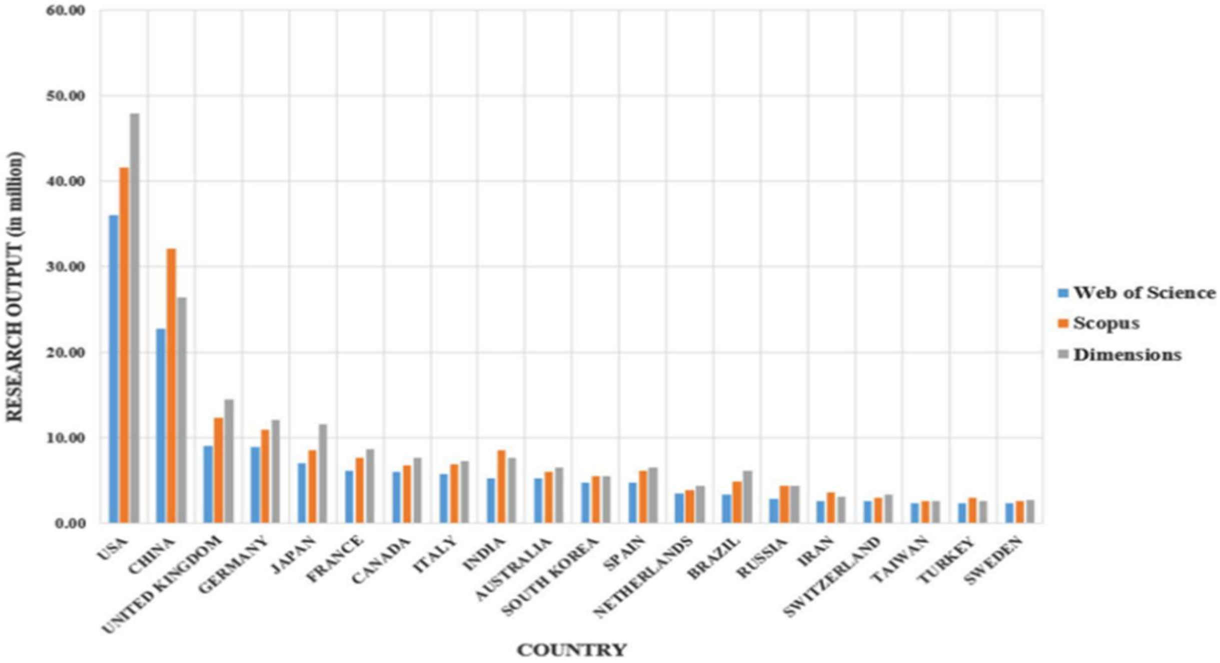

Figure 8 Research output in relation to countries for the databases, adapted from (Singh et al., 2021)

The search terms applied for the SLR has been selected based on the preliminary literature review. This yielded that the general term “Matrix-Structured Manufacturing System” was initially applied, although more and more commonly, the term “Matrix Production” was also applied interchangeably. The SLR has therefore applied the search term *“Matrix-Structured Manufacturing System” OR “Matrix Production”*, where the “OR” is applied as a logical operator to expand the search. From the preliminary literature research, it has also been clear that the term “Matrix Production” is generally applied in multiple fields, especially within cell biology. To account for this, all results including “cell” has been removed, in order to initially minimize the amount of faulty results. In Paper B, a brief literature research was performed to ensure papers regarding the work cell in MMS have not yet been covered. In this way, the search term does not exclude papers that focus on the individual work cells in a MMS. The final search term for the SLR can therefore be seen in Table 2 with specific modifications in regards to each database. The general search term can be described as follows.

(“Matrix-Structured Manufacturing System” OR “Matrix Production”) NOT “cell”

When performing the identification of papers, it is essential to highlight that the search has been refined, so that it only covers publications from 2014 to 2022. This is due to the first publication by Greschke et al. (Greschke *et al.*, 2014), coining the term Matrix Production. With this search refinement and the search term as defined above, a total of 595 records have been identified from the four databases. The specific amount of records from each database can be seen in Table 2.

Date	**Database**	**Search terms**	**Search refinement**	**Number of Articles**
15/06 – 2022	Sciencedirect	”Matrix-Structured Manufacturing System” OR ”Matrix Production” NOT Cell	Year 2014-2022	197
15/06 – 2022	Web of Science	”Matrix-Structured Manufacturing System” OR ”Matrix Production” NOT Cell	Year 2014-2022	213
15/06 – 2022	IEEE Explore	("All Metadata":"Matrix-Structured Manufacturing System") OR ("All Metadata":"Matrix Production") NOT ("All Metadata":Cell)	Year 2014-2022	5
15/06 – 2022	Scopus	(TITLE-ABS-KEY ("Matrix-Structured Manufacturing System") OR TITLE-ABS-KEY ("Matrix Production") AND NOT TITLE-ABS-KEY (cell))	Year 2014-2022	180
	Total record of articles from 4 databases			595

Table 2 Search Terms and Database overview, Adapted from Paper D

Based on these identified records, the PRISMA 2020 statement can be visualized as seen in Figure 9.

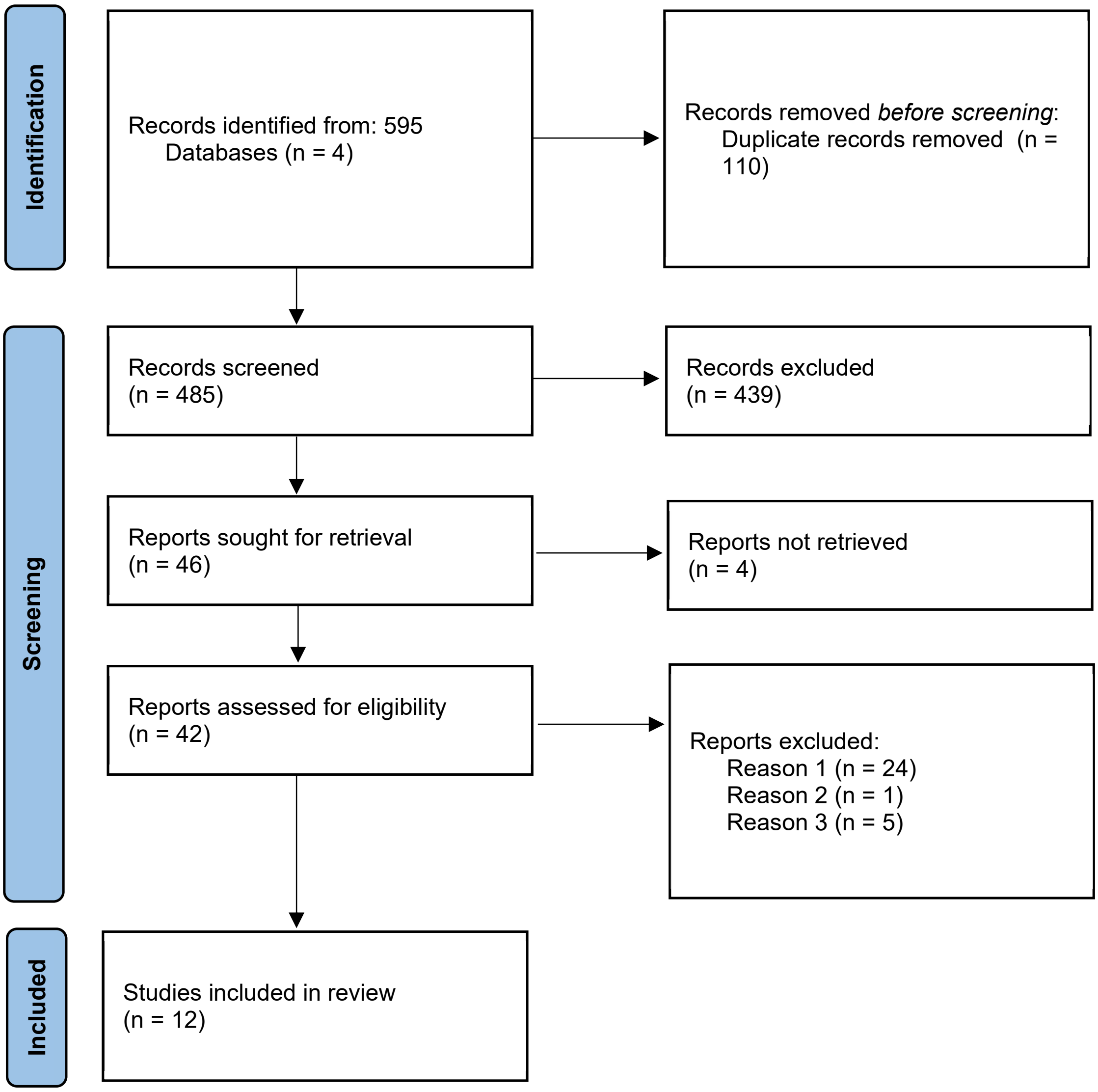

Figure 9 PRISMA figure, adapted from Paper D

These records have afterward been imported into Mendeley, removing 110 duplicates. As a result thereof, 485 records have been screened by the PhD student. The screening criteria are based on the following prioritized list:

1) Where was the record published?
2) Did the title of the record fit the goal of the SLR?
3) Did the keywords fit the goal of the SLR?

As the clear majority of the papers were targeted the health, materials science, or programming fields, 439 records were excluded. 46 records did, though, based on the journal or proceeding, the title and the keywords show some kind of connection to the goal of the SLR. Out of these 46 records, only 42 were retrievable. The four remaining records were abstracts for either a track during a conference or a workshop at a conference.

With the 42 records retrieved, they were further assessed based on the abstract and browsing through the paper with increased attention to the conclusion. This assessment led to 30 records being excluded for three reasons. The majority (24 records) was excluded, as they were not related to the research question, despite the journal, title, and keywords providing hints thereof. The second reason for records being excluded was due to it being written by the PhD student and co-authors (Nielsen, da Silva and Yu, 2020). The final reason for records being excluded was the original language of the record not being English, despite an English abstract being available. This yields 12 records being included in the SLR that answers RQ1 in section 4.1.

3.3 Case Study

In this Phd project, case studies have been a crucial methodology to answer RQ2 and RQ3. Common for the case studies performed is the focus on a single case, rather than a multitude of different cases. This allows an in-depth investigation and clear boundaries for the controllable variables, however also introduce an uncertain foundation when providing a generalized approach based on the case studies. Yin though argues that a single case study can be applied when facing an extreme or unique case (Yin, 2018, p. 50). Additionally, the case studies have been performed in two different settings; in a laboratory, and in a company. This allows for a more strict control of variables in the laboratory case study, while a more realistic and applicable case study with a company case study. Yin propose a general approach to performing case studies (Yin, 2018, p. 1). It is important to highlight that the model by Yin has provided great inspiration, especially in regards to pilot studies prior to that actual case study.

In this kappa, the description of a case study is adopted from Johansson. Johansson summarize it as “The case study should have a 'case' which is the object of study. The case should

- be a complex functioning unit,
- be investigated in its natural context with a multitude of methods, and
- be contemporary.” (Johansson, 2007)

Furthermore, the case studies can be of different types. Yao summarize the types as Exploratory, Explanatory, or Descriptive, and Intrinsic, Instrumental, or Collective (Yao, 1997). The three case studies applied in this PhD project tend all to be of a more explanatory nature with an instrumental aspect to it. Common for all types of case studies is the need for triangulation, ideally of data sources, evaluators, perspectives on the data, and methodology (Yin, 2018, p. 128). This ensures that the results from the case study are validated and verified. Triangulation is addressed further in section 5.5, where different types of triangulation is discussed in relation to each research question.

To further extend on case studies in an engineering context, Davis and Yadav summarize different aspects and variations of case studies in an engineering context (Davis and Yadav, 2014). One aspect is whether the case is of macro-context or micro-context (Davis and Yadav, 2014). Where the macro-context focus on the exploration of a problem over longer time periods and from multiple perspectives, the micro-context focus on smaller parts of a larger problem. Runeson and Höst present guidelines for performing case studies in software engineering, where they refer to three types of case studies: 1) positivist, 2) critical, and 3) interpretive (Runeson and Höst, 2009). Finally, Lee and Rine base their case study design for software engineering on (Yin, 1994), and highlights five important components of a case study approach: 1) a study's questions, 2) study propositions, 3) Unit(s) of analysis, 4) the logic linking of the data to the propositions, and finally 5) the criteria for interpreting the findings (Lee and Rine, 2004).

Common for all case studies performed throughout the PhD study has been the micro-context approach. Each case study each contribute to address the overall RO, of how to operationalize MMS. This implies, as experienced that the time frame is typically more limited compared to a macro-context approach, as well as the challenge has solely been addressed from one perspective. This is crucial to highlight, as this raises the need for triangulation in order to increase the credibility of the study. This is further discussed in section 5.5. Additionally, the case studies are of a positivist type, as they search for evidence to support the study propositions by for example measuring variables.

3.2.1 Laboratory Case Study

The laboratory case study perfomed in this PhD project targets the explanation on how to design products for MMS. To sufficiently investigate this, the case study has been divided into the following parts. It is crucial to highlight that the process is not strictly linear but iterative and parallelized in some aspects.

- Initial Literature study
- Conceptual development
- Experiment
- Theory generation

The initial step of this case study is the literature study based on the research question. The initial literature study has a more scoping purpose, identifying the literature within product design for MMS. This naturally functions as an extension to the current knowledge foundation on MMS, where the research gap has already been identified. The scoping review has furthermore been extended into Design for X (DfX), such as Design for Modularity, Design for Robot Assembly, Design for Manufacturing, etc. to provide a sufficient knowledge foundation within this field. In this way, the research gap is justified, as visualized in Figure 10. As the case study has progressed, the literature study has been extended and performed in parallel, although with less efforts towards the end. The key findings, primarily identifying the research gap, from the initial literature study can be found in Paper C.

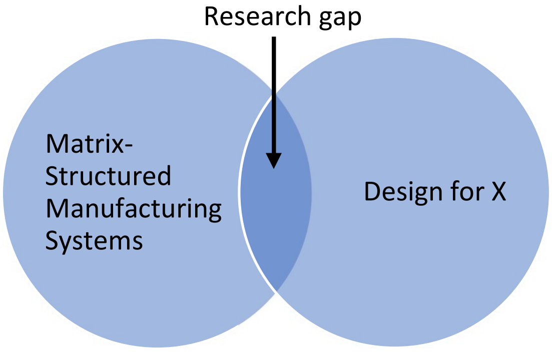

Figure 10 Research Gap (MMS and DfX)

The conceptual development has primarily been performed in a continuous, deterministic simulation environment from Visual Components, as well as a Computer-Aided Design (CAD) software, Siemens NX. The development has been twofold, developing partly the MMS work cell, and partly the product design. As identified in Table 1, high levels of product flexibility are enabled by the work cell design, thus forming a natural starting point for the development. Though, as a foundation for the work cell design, boundaries for the physical dimensions, as well as process steps for the product, have been established. Based on these boundaries, the work cell design is initialized through divergent thinking, using tools such as brainstorming to maximize the process and machine flexibility in the work cell. As part of that exploration, Visual Components has been used to enable convergent thinking for selecting the appropriate solution. Through this qualitative simulation perspective, the knowledge has furthermore increased earlier in the project, yielding a better foundation for doing important decisions, when the work cell is built physically. This is furthermore illustrated in Figure 11 (figure simplified and modified by adding the blue arrow from (Olsson, Ahrengot and Attrup, 2019, p. 60)), where simulation as a methodology translates the knowledge curve in the positive Y-direction, indicated by the blue arrow. Furthermore, the simulation also possesses a quantitative perspective, as described by Eldabi et al. (Eldabi *et al.*, 2002), as it facilitates the performance evaluation of various solutions. Although this is described in more detail in section 4.2, an example of this is the implementation of an industrial robot in the MMS work cell, developed in the Smart Factory Laboratory at the University of Southern Denmark in Sønderborg.

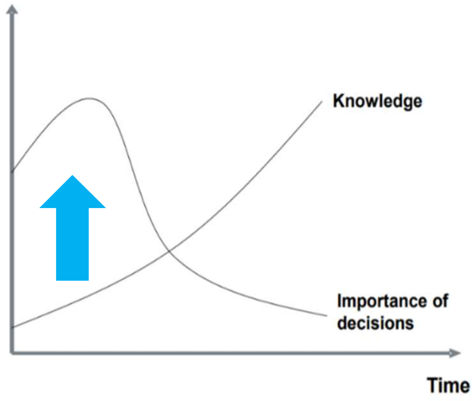

Figure 11 Relationship between knowledge and importance of decisions in relation to time in a project. Simplified and modified by adding the blue arrow from (Olsson, Ahrengot, and Attrup, 2019, p.60)

For the conceptual development of the product design, two initial products have been developed to be assembled in a simulation model of the MMS work cell. As part of the boundaries for the work cell design, the processes are targeted unit assembly operations of smaller electronics and their enclosures. These product designs, illustrated as Product A and Product B in Paper C, were designed in a CAD program and the individual components were assembled digitally to perform simple mechanical tests on fit, size, space, and similar. With the developed components in CAD, the components were imported into the continuous, deterministic simulation environment to perform first the qualitative analysis on exploring different assembly sequences, operations, task distribution, etc. and evaluating these through a quantitative perspective with focus on the performance evaluation. This pilot study serves as the knowledge foundation for developing a proposed “Product C” from Paper C that will used in the experimental part of the case study.

Based on the literature study on DfX as well as the knowledge acquired from the conceptual development, different methodologies have been applied to develop “Product C” from Paper C, initially in a CAD program and afterwards imported to the continuous, deterministic simulation environment. In the simulation, solely a quantitative analysis where performed, evaluating whether the improved design yields a better performance. To triangulate the data, the assembly process must be performed on the actual laboratory setup to achieve actual process data. This serves the purpose of validating the simulation model, as well as generating more stochastic data that represents reality better than deterministic data. To achieve another set of stochastic data, to further strengthen the data triangulation, a stochastic, discrete-event simulation tool like Siemens Tecnomatix Plant Simulation could be applied. Despite the data source for the stochastics would be grounded in the two other data sources, thus not being an independent data source, it would provide a stronger numerical foundation, exploring worst- and best-case scenarios in much more depth. It is though crucial to take into account the dependent data foundation and adjust for potential bias by continuously adjusting the stochastics when new datasets are available from further experimentation.

When the triangulated data has yielded an improvement compared to the initial dataset from the conceptual development, theory can be generated. In this case, it relates to the methodology of designing products for MMS that is the key contribution of Paper C. The theory generation part of the case study ensures a broader application than the specific case study. The learnings and process is therefore standardized to fit other applications. In this stage, triangulation is also crucial to verify and validate the results. In this case, this has been performed through qualitative, unstructured interviews with subject matter experts to the extent where possible. Ideally, a multitude of cases could also verify and validate the results, although due to the limited integrations of MMS combined with the intensive resources linked with these case studies, it has been yielded unfeasible. Finally, the publication of Paper C in a peer-reviewed academic outlet, Procedia CIRP, further verifies the generated theory.

3.2.2 Company Case Study

In the PhD project, two company case studies have been performed with a Danish manufacturer of industrial automation equipment. The company has implemented a MMS in their unit assembly that follows a one-piece order flow. As the products are designed with the possibility of potentially hundred thousands of combinations customized by the customer through an online configurator, the demand is uncertain. MMS therefore address these flexibility aspects, as identified in Table 1, in an efficient manner.

MMS Work Cell Design

This company case study was performed to address the explanation of how to design work cells for MMS. As the performance of the manufacturing system is strongly linked with the performance of each work cell, it is a crucial aspect to investigate in the pursuit of operationalizing MMS. To research this, the company case study has been performed, following the parts below. Similarly to the laboratory case study, the process has not been linear, but parallelized and iterative.

- Literature study
- Laboratory case study
- Theory generation
- Experiment

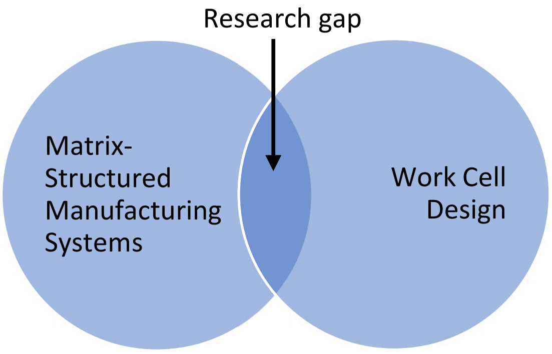

Figure 12 Research Gap (MMS and Work Cell design)

Similar to the laboratory case study, the purpose of the literature study has been on scoping, and justifying the research gap as seen in Figure 12. The literature study has been performed with the general foundation of MMS, and special attention to the work cell design research area. Additionally, the focus on flexibility has been investigated partly in literature, but also with a more commercial aspect, as actual implementations of innovative manufacturing equipment rarely are document in literature. For that reason also patents have briefly been investigated, although without any important findings. As the case study has progressed, the literature study has been continuously extended to account for new literature as well as new aspects identified during the case study.

The following part of the case study is an extension to the laboratory case study, where especially the conceptual development of the work cell has been further developed to serve as the foundation for the experiment on the company case study. By combining parts of the laboratory case study with the company case study, it is ensured that the pilot study prior to the experiment has reached a higher maturity level, thus providing a more accurate result to the experiment. Through the conceptual development of the work cell, several considerations on the flexibility aspect has been investigated and implemented into the laboratory demonstrator that has been verified and validated using continuous, deterministic simulations.

Based on the extended laboratory case study, a design approach for MMS work cells has been proposed. The theory has been generated by generalizing the design approach of the MMS work cell and increased focus on the process and product flexibility aspects. Furthermore, strategic and business-oriented parameters have been taken into account, broadening the field of applications as well as further addressing the other flexibility types. Prior to the pilot study, the initial design approach has been discussed with subject matter experts for early evaluation. This evaluation primarily focuses on whether the design approach balances a sufficiently broad coverage and not being too general, thus applicable for all manufacturing system paradigms. On this foundation and with the feedback from the subject matter experts, a brief pilot study has been performed to verify the design approach prior to initializing the experiment.

The purpose of the experimental part of the company case study is therefore to verify and validate the theory generated from the extended laboratory case study. The proposed design approach has therefore been tested in the company to investigate whether the design approach yields a result similar to the developed work cells in the company. In order to ensure that the experiment yields a correct result seen from a company perspective, the outcome of the design approach has been evaluated by a company subject matter expert through an unstructured interview. Furthermore, as the laboratory demonstrator and the developed work cell in the company case study differ drastically but yield validated results from the design approach, this ensures a sufficient theory generation.

Control System Architecture for MMS

This company case study was performed to address the explanation of how to control a MMS and the flexibility that this manufacturing system enables. This aspect is crucial, as it relates to the transition from designing a manufacturing system to the operation of it. The company case study has been performed with the same company as the previous company case study, thus efficiently leveraging the previous knowledge into a new perspective. The following steps have been performed to complete the case study.

- Conceptual Development
- Literature Study
- Theory Generation
- Experiment

The conceptual development for this case study was initialized by a personal reflection based on the two prior case studies on how to control the flexibility aspects through simulation. As the idea of having simulation control the physical environment in a computer-integrated manufacturing setup is far from new (Bilberg and Alting, 1991), the challenges of software and execution stability remain unsolved. With the recent advances in Reinforcement Learning (RL), the personal reflection and early investigation of the development of RL in a stochastic, discrete-event simulation environment, the foundation for exploring the topic further was built. To acquire the practical competencies for developing a conceptual model, a research visit at Aalborg University (AAU) in the Department of Materials and Production was planned. During the research visit, a small project was formed to explore how to control the material handling and machine flexibility in MMS using RL. Throughout the execution of the project with AAU, dialogue with the other researchers at AAU ensured constant learning and co-reflection that has supported theory generation.

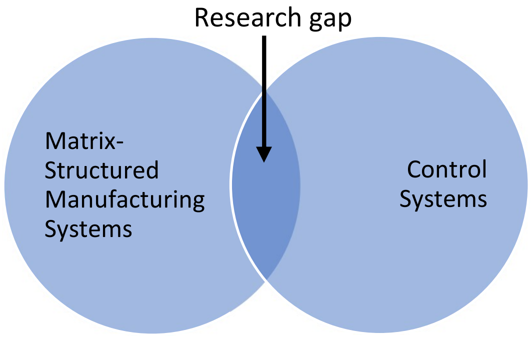

Figure 13 Research Gap (MMS and Control Systems)

Based on the conceptual development, a literature study has been performed. The purpose, other than identifying the research gap as illustrated in Figure 13, is to expand the knowledge on how to transition from design to operations by addressing the control system architecture. The literature study has been performed following an exploratory approach, where especially snowballing – investigating the references of a relevant paper to expand the literature study – has been critical. Later in the company case study, the literature study has also been performed together with a PhD student from AAU with expertise within control of manufacturing sytems. This has drastically leveraged the knowledge, thus also the theory generation.

The theory generation has been performed in strong collaboration with a PhD student and assistant professor from AAU, as well as an associate professor from SDU. All collaborators have a strong understanding of the company, hence a general understanding of the specific case was present and served as the basis for the theory generation. Furthermore, a thorough understanding of MMS was present. Through initially divergent thinking, key elements of a control system architecture targeted MMS were outlined, using tools such as brainstorming. Initial discussions addressed partially structure of the control system architecture (centralized, decentralized, or hybrid), as well as the level of control needed. This divergent approach was heavily supported by the the current literature as well as the expansion of it motivated by the discussions. Convergent approaches were though applied through investigating how a control system architecture for the company case would be developed. Based on this foundation, the experiment has been developed and proposed, as seen in Paper A. Through the experiment, the control system architecture has been verified and validated.

The experiment verifies and validates the proposed control system architecture by presenting an implementation design in a company case setting. Through the experiment development and execution, the results are triangulated through interaction with a company representative, as well as through a peer-review process in Computers in Industry. Through the implementation design, the generic theoretical contribution is furthermore elaborated on; hence the reflections on implementation are applied to refine the theoretical contribution. This is further described in Paper A.

4. Results

This section presents the results of the research questions in the kappa, based on the followed methodologies from the previous section. The first section addresses how MMS facilitate flexibility, as a summary of Paper D. Based on the results from the SLR, the following section investigates how to design products and the work cell in a MMS, thus summarizing Paper B and Paper C. Finally, to fully benefit from the flexibility enabled by MMS, the control aspect is addressed, summarizing the findings from Paper A.

4.1 Flexibility and MMS

MMS as a paradigm introduce high levels of flexibility by design, as identified in Table 1. It is though crucial to investigate how to fully benefit from the different types of flexibility, and how MMS make this flexibility easier to accomplish. Based on the SLR from Paper D, 12 papers have been included in the review to address how MMS facilitate flexibility, as seen in Table 3. The 10 types of flexibility summarized by ElMaraghy (ElMaraghy, 2005) will serve as the foundation for this analysis, as seen in Table 3. This table highlights how the current literature presents MMS in relation to the different types of flexibility.

#	**Reference**	**Machine**	**Material Handling**	**Operation**	**Process**	**Product**	**Routing**	**Volume**	**Expansion**	**Control Program**	**Production**
1	(Schönemann *et al.*, 2015)		X	X			X	X		X	
2	(Filz *et al.*, 2019)		X				X				
3	(Fries, Wiendahl and Assadi, 2020)		X				X				
4	(Göppert, Rachner and Schmitt, 2020)		X		X		X			X	
5	(May *et al.*, 2020)				X	X					X
6	(Trierweiler, Foith-Förster and Bauernhansl, 2020)		X	X	X		X	X			
7	(Li *et al.*, 2021)									X	
8	(Schumacher, Weckenborg and Spengler, 2021)		X	X			X	X			
9	(Stricker *et al.*, 2021)			X			X			X	
10	(Fries *et al.*, 2022)									X	
11	(Schumacher, Weckenborg and Spengler, 2022)	X	X	X							
12	(Zhang *et al.*, 2022)		X				X			X	

Table 3 Flexibility in MMS based on SLR, adapted from Paper D

Based on the SLR, it can be analyzed that MMS facilitate different types of flexibility, where specifically material handling, routing, operation, and control program flexibility receive great attention in literature. The material handling and routing flexibility types are facilitated through the use of transportation, typically AGVs. It is though essential to highlight that other means of transportation, such as autonomous mobile robots, manual transportation, or even flexible conveyor solutions, can also enable these types of flexibility. While the topology and means of transportation yield, in some instances, a disadvantage of taking up larger areas of the shop floor, the option of selecting different types of flexible transportation allow practitioners to adapt to the given circumstances, while still implementing MMS and achieve the flexibility benefits that this manufacturing system paradigm facilitates.

The operation flexibility also receives great attention in literature. The operation flexibility is deduced from the reconfigurability of the different work cells, as all work cells, in theory, can perform all processes needed to produce all product variants. Therefore, the number of different processing plans are, theoretically, equal to all possible combinations of processing plans. This is also linked to the material handling and routing flexibility, as these means of transportation allow for the operation flexibility to be physically realized, by dynamically transporting parts and tools around. The reconfigurability aspect of the work cells, does however also yield weaknesses. Especially the cost of both work cells and the customized tools that need to be adaptable to the work cells, decrease the likelihood of adopting MMS, despite these elements are enabling factors of operation flexibility. On the other hand, the customized tools that fit all work cells, can also be efficiently shared between the different work cells, and thus ensure a higher tool utilization. While this does limit the operation flexibility in practice, when all work cells does not have a full set of available tools, it can be considered an efficient way of balancing cost and performance, and yield opportunities for lowering the expansion flexibility barriers.

The control program flexibility is an essential part of MMS, however primarily as an enabler for the remaining types of flexibility that MMS facilitate. The control program flexibility, practically realized through a dedicated control system architecture, as proposed in Paper A, serves the purpose of efficiently orchestrating the many elements of a MMS, for example AGVs, work cells, processing plans, reconfiguration, etc. The control program flexibility therefore does not only allow the different types of flexibility to be realized both on a macro and micro basis, but also to reach the potential of these flexibility types. In the proposed control system architecture from Paper A, a centralized control system architecture is proposed to enable the control program flexibility. This centralized approach does however yield the weakness of limiting the expansion flexibility aspects of MMS. The centralized control system architecture will need to be adjusted and modified in case new tools, work cells, products, or similar are added to the system, thus complicating the ease of expansion. It is though from Table 3 also clear that the expansion flexibility, does not receive attention in literature. As described in the news paper article in Ingeniøren, Danfoss Drives A/S adopts a MMS (*Danfoss gentænker fabrikken fra blankt papir | Ingeniøren*, no date). The article furthermore states that the work cells are designed to be moved and recommissioned within 48 hours. Based on this, the effort and cost of expanding the manufacturing system, thus addressing the expansion flexibility, is low seen from a hardware perspective, while the, as discussed, software perspective from a centralized control program flexibility aspect yields more difficulties.

Comparing Table 1 and Table 3, it is clear that the literature does not yet cover all aspects of the flexibility types that MMS can potentially facilitate in full details. Especially the literature on machine, process, product, volume, expansion, and finally production flexibility in a MMS does not fully reflect, how MMS facilitate these types of flexibility. At the same time, many of these flexibility types are enabled through technological implementations, and thus based on strategic decisions, and not directly linked to the manufacturing system paradigms as a facilitator of flexibility. For example the machine flexibility that despite it not being enabled to a high degree, can be integrated by the use of smart toolchangers for the robotics operations, standardized mechanical, electrical, and software-based interfaces, etc. To leverage the benefits of machine flexibility, strong design guidelines for the work cells as well as tools are needed, such as proposed in Paper B.

In relation to process and volume flexibility, this is enabled through the reconfigurable, standardized work cells. As each work cell can be individually configured, the manufacturing system can in this way produce a high mix of products at the same time. This is therefore enabled by the definition of the paradigm, however physically realized through technical solutions, similar to those that enable machine flexibility. In relation to the volume flexibility, the possibility of dynamically reconfiguring the work cells in the manufacturing system ensures that key performance indicators (as part of the control system architecture), such as overall equipment efficiency, throughput, service levels, etc can be met no matter the expected product demands. In practice, this can be exemplified by only equipping a certain number of work cells with tools, thus ensuring that the equipment efficiency of the activated work cells are meeting the production expectations. Similarly, in case an unexpected huge demand of a certain product is experienced, the work cells can efficiently be reconfigured to only produce (parts of) the given product. Limitations of available tools do though apply for this consideration, however it also implies that MMS in a theoretical context has the opportunity to be considered a high mix high volume manufacturing system under these conditions and considerations.

Finally, the product and production flexibility are also linked to the paradigm as an enabler, where especially the work cells are essential, however also the product design approach, as described in Paper C. When introducing a new product variant, based on the product design approach from Paper C, a new tool can also be designed to account for processes that the current manufacturing system cannot perform. While this does indeed pose limitations, for example in terms of machine safety, software reconfigurability, etc. the capital expenditure is considerable smaller compared to other manufacturing system paradigms, where separate machines might need to be added to the system. This is therefore also an enabler of production flexibility, however the cost and effort of implementing drastically different products with more safety concerning processes, such as welding will need to be further researched to verify and validate this perspective. In general it can though be highlighted that MMS facilitate many types of flexibility due to the typically integrated technological aspects, but also especially due to the manufacturing system paradigm.

4.2 Design of MMS

The results for the second RQ is based on partly a laboratory case study and partly a company case study, as described in section 3.3. The key results from the laboratory case study and the company case study is the development of two appraoches for designing respectively the products in a MMS and the MMS work cells. The section is based on Paper B and Paper C.

The initial literature research as well as the theoretical background in section 2.2 indicate that while the current literature is targeted the design of MMS on the manufacturing system level, little efforts have been performed on the work cell level, as well as the product level. As the manufacturing system differs drastically from previous paradigms, as identified in Table 1, current approaches for designing the work cell and products for it are not sufficiently applicable to enable the full benefits of MMS. As the product design and work cell design inevitably are co-dependent, the actual implementation depends on the specific circumstances. During the PhD study, the work cell has been developed initially, although with a clear idea of the product parameters, such as operations, dimensions, and similar.

4.2.1 Work Cell Design

In paper B, a design approach is presented that assists the decision-maker to design a MMS work cell. The four-step approach, as seen in Figure 14, includes a product family analysis and an analysis of the needed level of automation. Based on this, an iterative process is initiated, starting from the work cell design that is afterward verified and validated in simulation. When the work cell design meets the specified requirements, the iterative process is terminated, and the work cell design can be physically constructed.

The first step creates a database based on an analysis of the product families that are planned to be produced in the MMS. The database contains information on each product within the product families and specify both production and product related parameters. These parameters, such as height, width, length, weight, tolerances, number of components, etc. are product related, while parameters such as processing time, process order, and similar are production related. It is essential to highlight that the production-oriented parameters also include an evaluation of the processes being value-adding, non-value adding, or essential, but non-value adding. The parameters are typically acquired from the Product Lifecycle Management (PLM) system, and can be identified in for example the Bill of Materials (BoM) and the BoP. This database serves to assist in the dimensioning of the work cells, but also as a foundation for the following steps, such as analyzing the level of automation needed. As the product portfolio might expand over time, so will the database. In this way, by following these steps, it will also be possible to quickly evaluate whether a new product design can be easily and cost-efficient produced in the manufacturing system. Hence, this step addresses product flexibility.

The second step determines the level of automation needed to produce the products in the developed database from the first step. To perform this analysis, it is important to evaluate three aspects; the projected production volumes for each product, the data from the database, and finally, the company strategy. The projected production volumes for each product are added to the database to serve as a reference database, as it will be used in the future steps as well. This aspect is used to evaluate what processes will be prioritized to be automated and what processes that are not used that frequently can be performed manually. When this aspect is connected with the production-oriented parameters of all products from the developed database, a solid foundation is created to evaluate the level of automation. This foundation is further supported by the company strategy, where considerations such as improved quality or lower cost can yield a competitive advantage. With these aspects in mind, a qualitative analysis can be performed to evaluate if the MMS work cells should be fully automated, fully manual, or a hybrid solution, such as collaborative. An optional, quantitative cost-benefit analysis can be performed to enhance the foundation for the decision further.

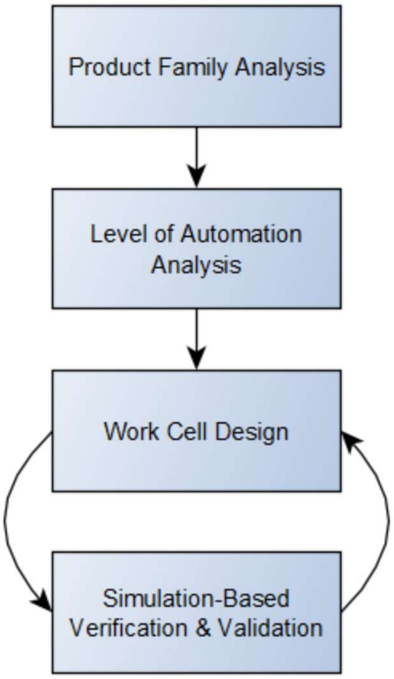

Figure 14 MMS Work Cell Design Approach, adapted from Paper B

The third step develops the work cell design and creates a digital prototype of the work cell. This step uses the current approaches either in the specific company or from the literature to develop the work cell design. Based on the developed database containing the product and production-oriented parameters, physical dimensions of the work cell can be determined, such as the payload of a robot. The production-oriented parameters enable the work cell design to evaluate the tools needed to accomplish the processes. Other aspects to consider in the work cell design include ergonomics, ease of maintenance, safety, and similar. When a sufficient work cell design has been reached, the digital prototype can be developed. Here, it is possible to perform simple tests, such as the reach of the robots, placement of fixtures, and similar. It is important to highlight that his digital prototype typically will be developed in a CAD program, thus the extend for these tests are limited.

The fourth step develops a simulation model to verify and validate the work cell design. This simulation model is created with the digital prototype as foundation, thus making it dynamic to include performance evaluations and more advanced tests, such as bottleneck analysis and gravitational impacts. This simulation is typically carried out in a deterministic, continuous simulation environment, such as Visual Components. The numerical foundation for the simulation is based on the data from the database developed in the initial step. If the simulation performance evaluations yield unsatisfactory results, an iterative process, returning to the third step on work cell design, is activated. If the simulation results are sufficient, virtual commissioning can be applied to develop the control behavior of the work cells. Thus, the work cells can be considered designed and ready for construction and afterward physical commissioning based on the virtual commissioning.

To further explore the work cell design, a laboratory case study has been developed. Although this laboratory case study addresses the product design, the work cell design is fundamental. The work cell, as seen in Figure 15, enables flexibility in several ways. This flexibility arises partly from the equipment applied and partly from the work cell design. Similarly, the product design is crucial, as it can minimize non-value creating tasks, such as tool changes and fixture changes, among others. This is further elaborated on in Paper C as well as the following subsection.

The proposed approach from Paper B, has been applied as a foundation for the creation of the work cell in the laboratory case study. The product family analysis from the proposed approach is similar to the product family analysis from Paper C and therefore serves as the same foundation, as the products produced in the work cell is the same as those of Paper C. For the level of automation analysis, a collaborative work cell is to be designed. The key motivation for this decision is the flexibility that an operator adds to a work cell. An operator can both easily adapt to new products and products, thus contributing with process and product flexibility. Furthermore, the collaborative work cell can be operated with one shift during normal demand conditions, and have the two remaining shifts being fully operated at the cost of a lower overall throughput. In case an increased demand arise, for example due to seasonal deviations, the option of adding operators on the two remaining shifts, enable volume flexibility as well. Based on this foundation and considerations, the remaining steps of the work cell design approach from Paper B is stated below.

The work cell, targeted assembly of smaller mechatronic products as presented in Paper C, encompasses six key components, as seen in Figure 15 that enables flexibility for adapting to products from multiple product families. The first component denoted “1” in Figure 15 is the collaborative robot (cobot) on a 7th axis. The cobot and operator can collaborate on the assembly tasks, independent of each other or without an operator present in the work cell. Furthermore, the 7th axis increases the reach of the cobot, allowing it to position itself in the ideal location for the given task. In this way, the cobot can perform tasks related to material handling, feeding the industrial robot cell, perform tool change on the industrial robot, change of fixture, and assembly work.

Another crucial part of the developed work cell is the local storage, denoted “2” in Figure 15. This local storage allows the work cell to store parts for assembly, consumables, and finished goods, but also tools. It is crucial that the storage solution can be utilized by the cobot and the operator, ensuring a strong collaboration. Additionally, an important feature of the local storage is the simplicity of replenishing and removing the finished goods and tools. In this way, the time to change product, product family, processes, and generally reconfigure is minimized.

Similarly, the tool changers on the cobot and robot, indicated as “3” in Figure 15, are of high importance for the flexibility in the work cell. The tool changers allow the robot and cobot to expand their capabilities, increasing the flexibility in the processes they can perform. Through this standardized interface, the tools can partly be shared between the robot and the cobot, lowering the initial investments on tools, but also allows for simple introduction of new tools to produce new products or product families.

The fixtures denoted “4” in Figure 15 ensures a fixed position for the cobot and robot to work on the product. It is designed for easy and quick exchange of custom fixtures for specific products or product families. This furthermore allows easy integration of new products or product families, as the standardized interface allows full flexibility. In connection with the operator presence sensors denoted “5” in Figure 15, the fixtures can furthermore be adapted to fit either robot assembly or assembly by the operator. With the operator presence sensors, it is possible to safely achieve the flexibility, such as scalability and adaptability that the operator brings.

The 6th key component in the work cell is the industrial robot cell. The industrial robot with a tool changer is the central aspect of this cell. As the industrial robot typically is drastically faster than the collaborative robot, this cell adds speed to the work cell. Additionally, it enables the possibility to perform specific processes in a safe manner, such as high-power testing, gluing with chemical compounds, soldering with lead-based materials, or similar. To ensure full flexibility, the industrial robot cell consists of similar components as the overall work cell, such as the standardized fixture and tool changer. In this way, not only redundancy is achieved, but also flexibility for the control software to select the most suited resource for the given task.

To further explore these levels of flexibility, a DT, corresponding to level two according to Madni, Madni and Lucero (Madni, Madni and Lucero, 2019), has been developed. Initially, the pre-DT, implemented as a deterministic, continuous simulation, has been applied to ensure an efficient work cell for both the operator and the cobot. By simulating the interaction and task allocation in a risk-free environment, it is possible to

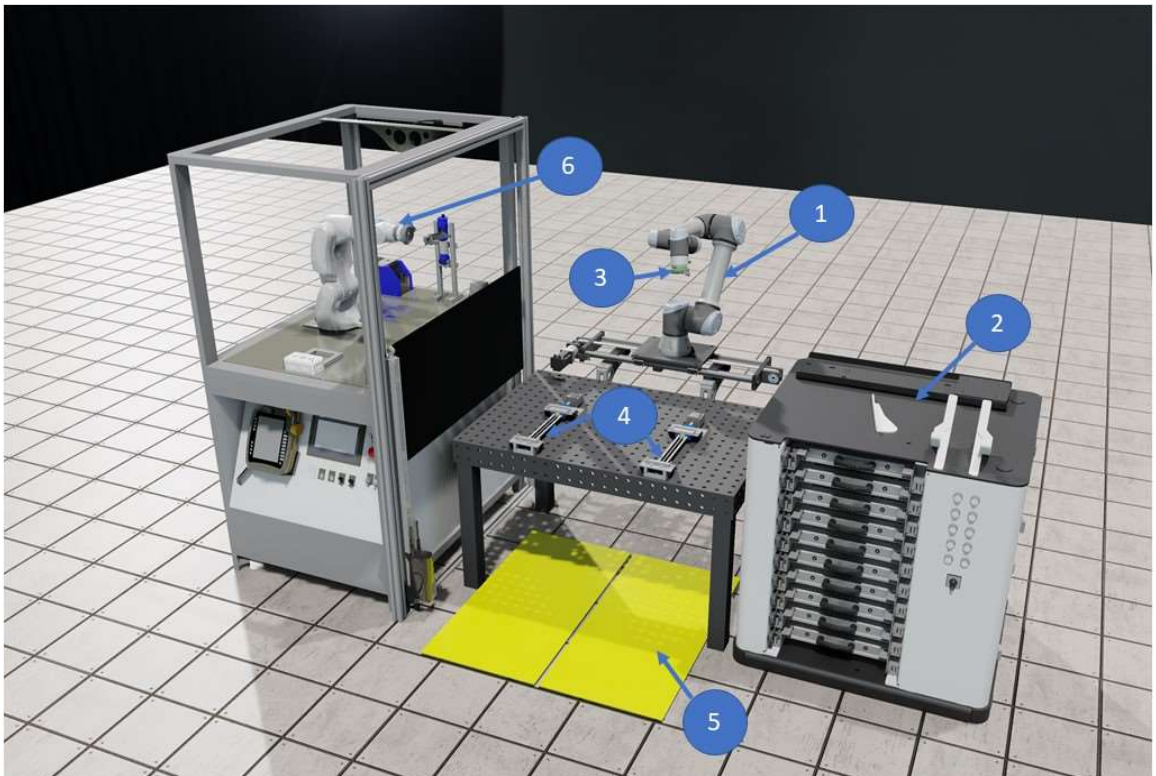

Figure 15 Visualization of MMS work cell from simulation

explore and evaluate the flexibility on multiple products and product families. The data from the deterministic, continuous simulation is afterwards applied in a stochastic, discrete-event simulation in order to explore the flexibility on the manufacturing system level. In this way, multiple types of flexibility, such as machine, routing, volume, and production flexibility, have been evaluated prior to actual implementation. When the pre-digital twin has reached a satisfying maturity level, bidirectional communication with the physical work cell has been established, allowing both control and monitoring from the simulations.

4.2.2 Product Design

In Paper C, a design approach for designing products and product families to be manufactured in a MMS is presented, as seen in Figure 16. The design approach consists of four stages that assist the decision-maker in optimizing the design for MMS and thoroughly verify and validate the results to ensure an efficient adaptation. It is important to highlight that the proposed design approach differ from existing design approach for module-based product families. The key difference, for example from (Gauss, Lacerda and Cauchick Miguel, 2021), is the indicator calculations that ensure that the design improvements result in a quantified optimization. Furthermore, the DT-based verification and validation enable the practitioner to further quantify the actual performance improvement. It is though also important to highlight that the proposed design approach does not replace existing methodologies, but combines these in the “Product Optimization” step.

The first stage analyses the product families and assembles the data in a database, similar to the work cell design approach in Figure 14. Ideally, the data are of the same origin and quality; thus, in practice, the two databases can be merged. This ensures that the design of the work cells and the design of the products are based on the same data foundation. The major difference between the two databases is that in the work cell design approach, the operations are divided into three categories, while in the product design, they are divided into two. In the product design approach, it is not distinguished between essential but non-value adding operations and non-value adding operations.

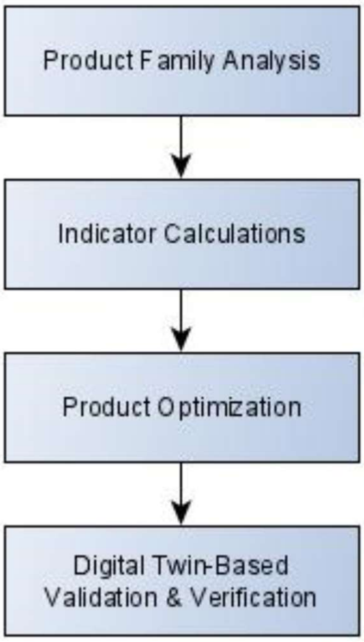

Figure 16 Product Design Approach, adapted from Paper C

The second stage calculates relevant indicators to provide a numerical foundation for optimization. The key indicator to calculate in this stage is the design efficiency, defined as the sum of all value-adding time as a percentage of the total time. By calculating this numerical value, it is possible to mathematically investigate what operations to optimize and numerically investigate the impact of, for example, removing non-value adding work. This numerical representation also allows for prioritizing optimizations in a cost-benefit analysis, as the cost of a specific process optimization quantitatively can be connected with a design optimization. Finally, the design efficiency serves as the foundation for comparing design improvements to the current design iteration.

The third stage applies current DfX methodologies to optimize the product design based on the developed database. It is essential to highlight that the product design optimizations are strongly connected with the work cell design, as, for example, the Design for Robot Assembly methodology will yield little to no improvements in a fully manual production. To evaluate the impact of the DfX methodologies on the product design, the design efficiency is calculated for the improved design to ensure a numerical foundation for the optimization. It is though essential to highlight that this numerical foundation at this stage is based on estimations and assumptions, thus yielding uncertainty in the actual optimization. Further verification and validation are therefore needed to ensure a sufficient foundation for the product design optimization.

The fourth stage uses a DT-based approach to verify and validate the product design. The stage is divided in two steps; a simulation-based verification and validation and a physical verification and validation. The first step utilizes a simulation model of the work cell to simulate the operations to be performed on the product. Here, the benefits of a deterministic, continuous simulation are applied to gain a quantitative perspective on the performance evaluation. In this way, the numerical foundation from the design efficiency calculations can be verified and validated in a risk-free environment and simultaneously provide a platform for exploring, thus increasing the knowledge in the project, as illustrated in Figure 11. To address the deterministic behavior and the shortcomings thereof, the second step connects the simulation model with the physical work cell to introduce the possible variance that is present in the real world. Through the bi-directional communication between the physical work cell and the simulation, the product design is verified and validated. This DT, corresponding to a level two DT by definition of Madni, Madni, and Lucero (Madni, Madni and Lucero, 2019), furthermore strengthens the simulation model, meaning future simulations are based on a better foundation for these quantitative assessments in the first step of the fourth stage. When the product design optimization has been verified and validated, the product design is ready to be implemented and commissioned in production.

It is crucial to highlight that one of the clear benefits of MMS that other paradigms do not enable is the possibility to utilize one of the work cells for experiments while the remaining work cells are still producing at their full capacity. This benefit, exemplified in the product design approach on stage four, step two with the physical verification and validation, invites continuous optimization through physical experiments. Additionally, as the work cells are standardized, these optimizations are universally applicable; thus, the deployment is a matter of duplication for a manufacturing system optimized performance.

4.3 Control of MMS

With a developed MMS, optimized with an ideal product and work cell design following the proposed approaches by Paper B and Paper C, a sufficient control system is crucial to leverage the different types of flexibility that the manufacturing system encompass. As described in Paper A, different types of control systems for manufacturing systems exist that also, to some extent, take into account the different types of flexibility. However, these control systems do not encompass the flexibility that is enabled by a MMS, as it differs from the remaining manufacturing system paradigms, identified in section 2.1. This means that the full flexibility potential of MMS is not enabled using the current control system architectures. This is further supported by the findings from Table 3.

Initial investigations on the use of RL in stochastic, discrete-event simulations yielded promising results in terms of applicability to control the increased flexibility. Here, RL was considered as a sufficient candidate to address the many degrees of freedom, or flexibility, that this manufacturing system can facilitate. While current control approaches, such as model-predictive controllers, indeed also are of interest, the complexity that this manufacturing system can possess, requires more advanced control approaches. Where solutions like a model-predictive controller will increase in computational calculations as the number of possible solutions increase, the RL approach will solely explore the complete solution space partially.

Connecting Siemens Tecnomatix Plant Simulation 16.0 through the Component Object Model (COM) interface with a Python script, the availability of open-source libraries can leverage the development, and thus the RL approach can be realized. In this regard, two aspects need to be addressed; standardizing the environment and selecting the RL agent library. While OpenAI gym is slowly becoming the standardized environment for multiple RL agent libraries to interface with (*Gym Documentation*, no date), different libraries for developing the RL agents exist, each with its advantages and disadvantages. Initially, Keras-RL (Plappert, 2016) was applied due to the strong integration with Keras – a deep learning library. However, due to the availability of certain algorithms at the given time, a switch to StableBaselines3 was initiated (Raffin *et al.*, 2021). This allowed for the appropriate inputs from the RL agent to train, and easy and standardized testing of different algorithms and their performance.

To further extend on this initial investigation, it is important to first describe the case more in detail and then highlight the critical aspects of the RL implementation. The initial investigation was centered around a small artificial case, the "environment" in RL terminology, of five work cells that have five different assembly configurations. This case focused on assemblying three similar products with only slight variations in the assembly time. Common for all products was the need for all five processes in order to be completed, however not in any fixed order. The initial investigation case therefore focused on how to control the material handling and process flexibility using RL. The possible paths for material flow can be seen in Figure 17. The initial investigation case allowed the environment to have an episode length of 24 hours.

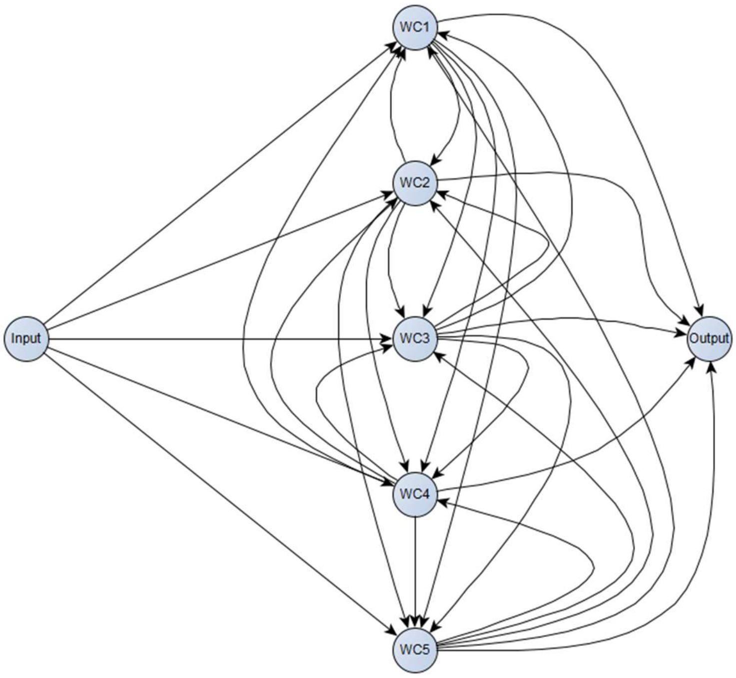

Figure 17 Possible material flow paths of initial investigation study

Generally, central terms centered around RL include the learning algorithm, the reward function, the observation space, step time, and the action space. For the initial investigation case with the purpose of controlling the material handling and process flexibility, the action space is defined as an array with five elements for the routing options, and five elements for the workcell configuration. Each element is furthermore a discrete value, either 1, 2, 3, 4, or 5. In the applied python script, this is realized using the MultiDiscrete function:

ActS= MultiDiscrete([5,5,5,5,5,5,5,5,5,5])

The first five elements are linked to the material handling, while the last five are linked to the workcell configuration.

The observation space has in the initial investigation case solely been selected to be the throughput of the system. While in hindsight the limited observation space gave several challenges, primarily as it is not representative of any manufacturing system to solely measure throughput as the only key performance indicator. Nevertheless, the observation space was therefore a discrete value that was connected to the Drain statistics in the Siemens Tecnomatix Plant Simulation environment. In this connection, the step time is important, as it determines how often the throughput of the manufacturing system is sampled (and how often new actions are performed). Two different step times have been applied in the initial investigation case; A time step equal to the episode length of 24 hours, and a time step of each event in the discrete-event environment. Clearly, this difference has hugely impacted the outcome of the RL agent, and especially the training efforts. The time steps are also important in relation to the calculation of the reward function. As the reward function in this initial investigation case is solely based on the throughput of finished products, the rewards are either sampled very frequently or only once, depending on the time step. This decision also clearly influences the training efforts, as described further in this section. It is therefore clear that the time step decision has a high impact on the training efforts. While these two time steps pose as two extremes, a rulebased approach, for example as proposed by Zhu et al., could yield training efforts reduction of up to 72% (Zhu *et al.*, 2022).

The final crucial parameter, to highlight in relation to the initial investigation case, is the learning algorithm. As the RL learning agent was implemented through Stable-Baselines3 (Raffin *et al.*, 2021), three different learning algorithms could be applied with the MultiDiscrete action space; A2C (Mnih *et al.*, 2016), PPO (Schulman *et al.*, 2017), and TRPO (Schulman *et al.*, 2015). As Stable-Baselines3 allow for easy exchange of different learning algorithms on the same environment, the three learning algorithms could easily be tested. However, due to the shortcomings of individually utilizing A2C and TRPO, the PPO learning algorithm was applied, as it combines the ideas from both to create a more efficient learning algorithm. The PPO learning algorithm was applied with the policy network, the multi-layer perceptron (MLP) policy, primarily due to availability in the selected library, and implementation of custom policies were out of scope for the initial investigation.

To reflect upon the initial investigation case, it is though crucial to highlight that the purpose of the initial investigation was centered around the feasibility of partly utilizing Siemens Tecnomatix Plant Simulation as the environment in RL, and partly how RL can control the flexibility in MMS. The reflections were primarily related to the observation space, reward function, and the time step, and how they interact with each other. Additionally, the reflections were also connected to the tools applied to realize the RL agents and environment. First of all, the limited observation space yielded several challenges, especially in relation to the training of the RL agent. As it partially does not represent reality on how many key performance indicators are utilized in a manufacturing system, it also creates a RL agent that is very reactive in behavior in order to achieve a higher throughput. In this connection, the initial investigation case did not include any setup times when reconfiguring, thus the RL agent could potentially reconfigure constantly, while the physical constraints of that would not be sufficiently modelled in the environment. To account for this, the observation space could therefore be expanded to include several more factors, such as a certain amount of future product orders, the utilization of the individual work cells, as well as the OEE, and intralogistic transportation cost. These aspects, in combination with a more detailed RL environment, should drastically improve the performance of the RL agent. Additionally, the time step should also be adjusted to more appropriately accompany the environment, and the observation and reward function. It is crucially to balance this parameter, as the two extremes applied in the initial investigation case either yielded unsatisafactory results. These results were caused by a too quick update, understood for example as a correct configuration and material flow but no product could yet be finished, or when the time step is equal to the episode length, the optimization task becomes static, as the action and observation space, along with the reward is only calculated once. In relation to the tools applied, future implementations would more thoroughly investigate different solutions in the initial stages, where especially commercially available solutions would be in scope.

Based on this foundation, the literature study, and the fruitful collaboration between AAU, SDU, and the case company, the following control system architecture for MMS has been proposed, as seen in Paper A. The control system architecture is described using the C4 model (*The C4 model for visualising software architecture*, no date). This model encompasses four different abstraction levels to standardize the visualization of a software architecture. The four levels describe the context, container, component, and finally code level of the software architecture. In this kappa, the first three levels will be used to describe the control system architecture for MMS, as the fourth level are heavily dependent on the actual implementation and the coding style of the programmer or software engineer, as well as the coding standards for the implementing company.

The context level generally explains the interactions between a proposed overall software system and external software systems, operators, or similar. As illustrated in Figure 18, the proposed control system dedicated MMS, called “Matrix Controller” (MC), functions as an addition to the existing architecture in a company, as it receives data from the Enterprise Resource Planning (ERP) system, or the optional Manufacturing Execution System (MES)¸ and processes it to be transmitted to the work cells and the AGVs or AMRs.

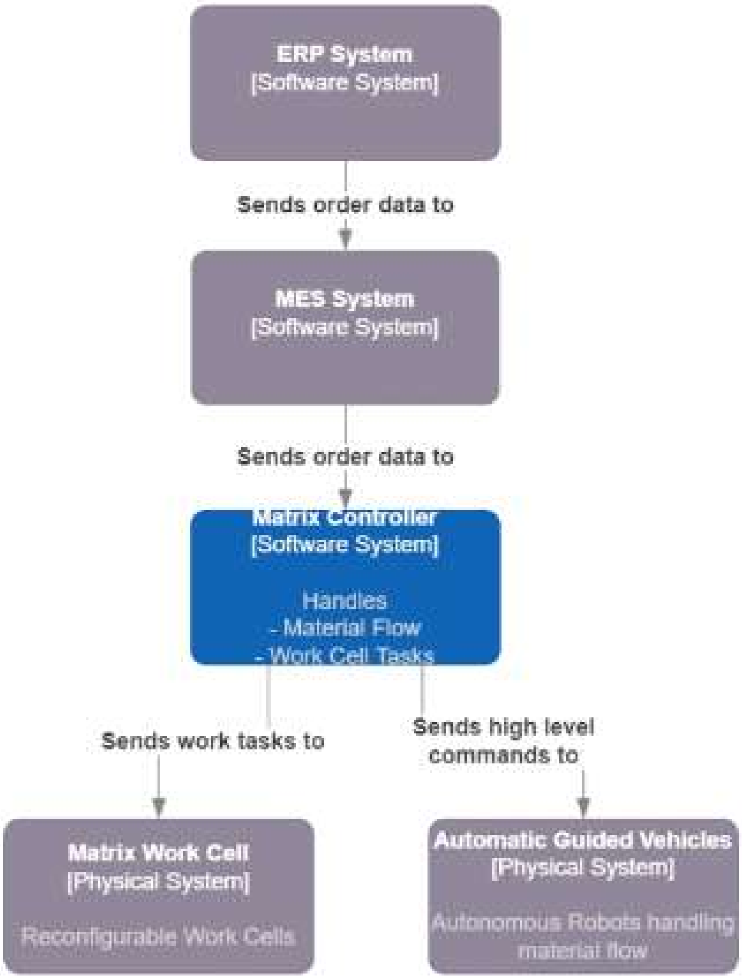

Figure 18 Context Level of Control System Architecture for MMS, adapted from Paper A (Nielsen et al., 2023)

The ERP system handles all the customer orders and produces a set of order data that is either processed further in the optional MES, or directly sent to the MC. It is important to highlight that the data quality and content is a determining factor for the need of the MES, as well as the actual implementation of the ERP system. Where some ERP systems are integrating MES aspects, the need for the MES is minimized, while less elaborated ERP systems will benefit from an implemented MES. After the order data has been processed in the MC, a set of work tasks and high level AGV or AMR commands are sent to the physical systems. The MC does therefore not replace any existing software systems, but simply provides the necessary software aspects for optimizing the MMS and the flexibility that this manufacturing paradigm enables.

On the second level of the C4 model, the container level is presented, where the MC is explained in more details. The MC consists of five software containers that all plays a crucial role in sufficiently controlling a MMS; a database, an Autonomous Matrix Manager (AMM), a simulation, a work cell controller, and a material flow controller. This is furthermore illustrated in Figure 19. The key software container is the AMM that handles the decision making aspects, while the remaining containers are of a supporting functionality.

The database container stores all raw data from the different systems and containers. This raw data includes the next 100 production orders, received from the ERP system, as well as the production data and routing information respectively from the work cell controller and the material flow controller. After this information has been analyzed by the AMM, and a simulation has been performed, the optimal simulation results are returned to the database container.

The AMM analyzes and makes decisions on the control of the manufacturing system. This container reads data from the database and prepares it for simulation. Based on the simulation results and other parameters, further expanded in the third level of the C4 model, a decision-agent makes a decision on how the optimal control of the MMS at the given state will be. This decision is afterwards prepared for the work cell and material flow controllers.

The simulation container performs stochastic, discrete-event simulations to optimize the control of the MMS. These simulations increase the knowledge foundation, as elaborated on in Figure 11, and explore the possible solutions to a greater extent. The simulation model can be developed using industrial simulation solutions like Siemens Tecnomatix Plant Simulation, and remotely executed with the new input data. To sufficiently utilize this data, the AMM prepares the raw data from the database in a standardized format suited for the specific simulation model. Based on the multitude of simulation experiments, the optimal solutions are stored in the raw database. It is crucial to highlight that the simulation model needs to be updated to sufficiently provide results of high data quality.

The work cell controller ensures efficient control and monitoring of the MMS work cells. With a functionality comparable to a supervisory control and data acquisition (SCADA) system, this software container is designed to control and monitor the MMS work cells. In this way, the work cell controller is solely receiving an input on what to produce and in what order, if and how to reconfigure, while the remaining tasks such as the execution of low-level commands are fully implemented in this controller. This can for example be a skill-based approach, such as proposed by Schou et al (Schou *et al.*, 2018).

The material flow controller manages the control and monitoring of the AGVs or AMRs. This solution can potentially be an off-the-shelf solution, or consist of customized software, such as proposed by for example Zhang et al (Zhang *et al.*, 2022). This controller receives data from the AMM and ensures sufficient control of the AGVs or AMRs, and sends relevant data back to the database container for inclusion in the simulation model.

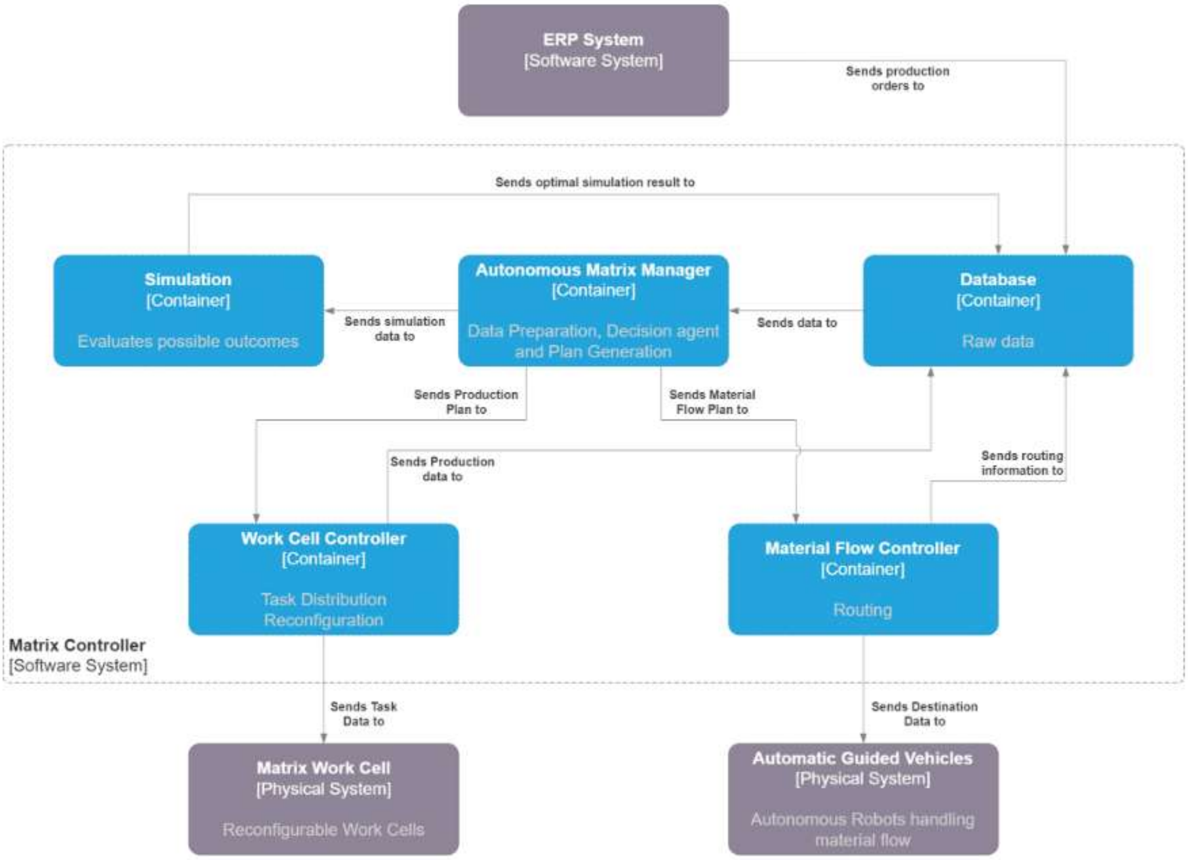

Figure 19 Container Level of Control System Architecture for MMS, adapted from Paper A (Nielsen et al., 2023)

On the third level of the C4 model, the component level is described, further describing the AMM in details. The AMM consists of three software components and two optional software components that combined performs the optimized decisions to improve the control of a MMS. As seen in Figure 20, these components include data preparation, a decision agent, and a plant generation component. To further strengthen the decision agent, a RL agent and training database can optionally be added.

The data preparation component imports the data and structures it for execution in the simulation module. This data preparation covers not only the data structure, but also the right datatypes to be applied in the simulation model. Simple tests can also be performed to, for example, address invalid processing times, human errors, or data conversion errors. The data can then be stored in JavaScript Object Notation (JSON) format for easy integration into the simulation solution.

The decision agent component performs the control decision based on simulation results. The algorithm implemented in the decision agent can vary depending on the products to be produced in the MMS. For simple operations with little requirements for control, an extended switch-case structure could yield sufficient results, where a more advanced manufacturing system might require AI-powered decision-making, either using (deep) neural networks or RL. Alternatively a model-predictive controller in combination with a reduced order model of the simulation can also yield sufficient results.

The plan generation component converts the decision to a task execution plan and a destination plan. This implies that the decision received from the decision agent is initially analyzed and split into work cell relevant data and material flow relevant data. Afterward, the data is prepared according to the format that the work cell controller and the material flow controller expects. Similarly to the data preparation component, this can also be stored in JSON format for standardized data transfer.

The optional RL training component and training database strengthens the decision agent and optimizes the decisions. By implementing the optional RL, the simulation data is used to continuously optimize the decision agent. As the stochastic behaviour of reality yields slightly different simulation results, the agent will over time asymptotically approach a dynamic programming scenario, as the state and solution space is fully explored. The training database is used for locally storing the necessary data for training the RL agent.

In this way, the proposed control system architecture can be developed and applied to more optimally control a MMS. Following the company case study in Paper A, this proposed control system architecture leverages the performance of a MMS, compared to a modified DML controller, and ensures a continuous improvement. In this way, the control system architure will improve performance over time, while in the initial stage still perform efficiently, as the decisions are based on stochastic simulations, thus a statistically strong foundation.

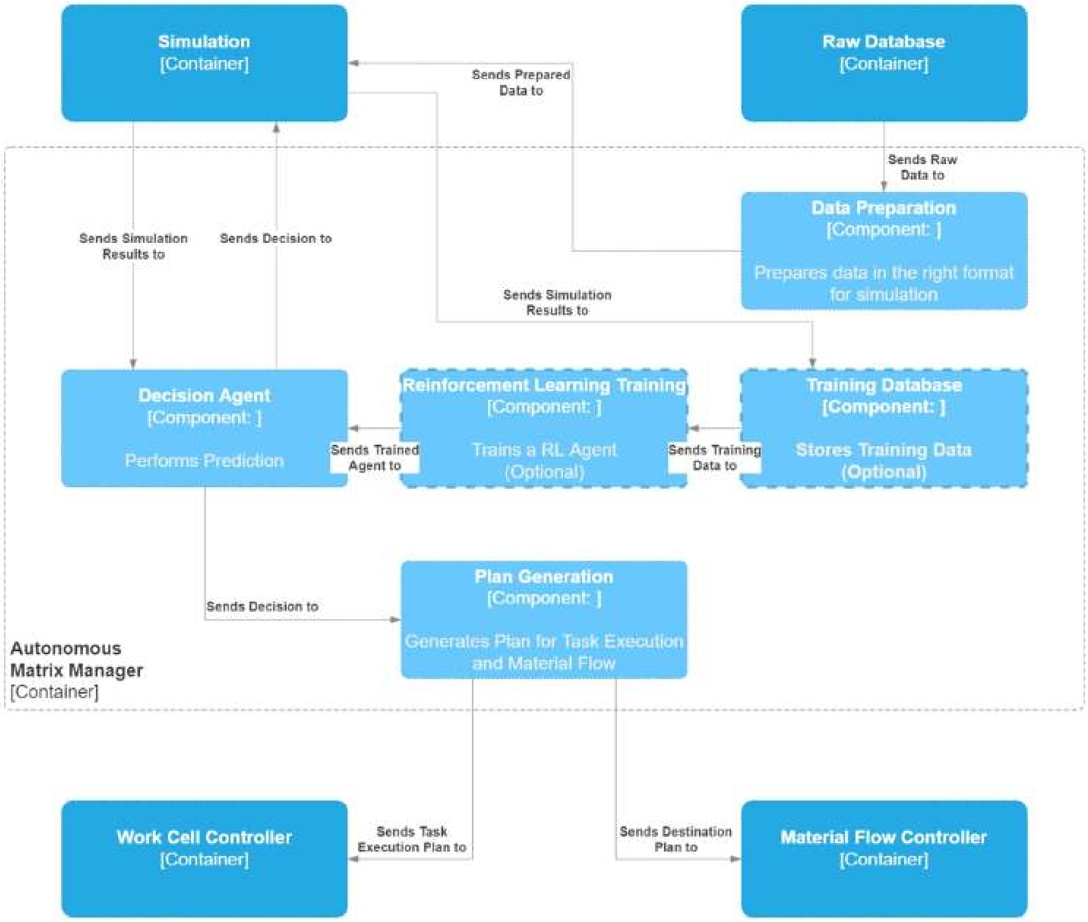

Figure 20 Component Level of Control System Architecture for MMS, adapted from Paper A (Nielsen et al., 2023)

5. Discussion

This section discusses MMS as an actor in supply chains (SC) and some of the enabling aspects that this manufacturing system brings through its flexibility. The section initially puts MMS into a SC perspective. Based on this perspective, MMS are discussed in relation to sustainability, and finally, how new business opportunities arise. With these topics as foundation, it is discussed if MMS can be regarded as a ‘manufacturing system of the future’. Finally, the research design is discussed and reflected upon.

5.1 MMS in Supply Chains

On the SC level, the strategic decision to implement a MMS brings several benefits with the flexibility that the manufacturing system facilitates. One of these benefits, resilience, has briefly been discussed in relation to MMS by Ihlenfeldt et al (Ihlenfeldt, Wunderlich, Susse, *et al.*, 2021). This resilience increases the manufacturing system resistance towards disturbances such as changing purchasing behavior, impacts of natural disasters, and similar. Additionally, it ensures a quick recovery to the initial equilibrium state. However, to fully benefit from the flexibility that a MMS enables, the SC also needs to sufficiently supply the materials, thus adapting to the changing purchasing behavior. This requires to a certain degree SC resilience (SCRES).

As identified by Adobor and McMullen, SCRES comprises of different capabilities, resilience types, and phases (Adobor and McMullen, 2018). Where MMS enables a high degree of adaptive capabilities, leading to an ecological resilience, engineering resilience and evolutionary resilience are still needed to fully enable SCRES. Implementing technologies such as blockchain through a DT-based approach, as presented by Nielsen, da Silva, and Yu (Nielsen, da Silva and Yu, 2020), the trust along the SC can be increased, thus strengthening the evolutionary resilience. Technologies such as Industrial Internet of Things (IIoT) can also strengthen this trust. Finally, the engineering resilience can be addressed through sufficient control, where especially agent-based simulations can provide a solid foundation for decision-making and analysis of different control approach, such as lean manufacturing (Adobor and McMullen, 2018).

These types of resilience furthermore impact the four phases of SCRES, summarized by Adobor and McMullen (Adobor and McMullen, 2018). For a MMS to fully benefit from the flexibility, the readiness phase of SCRES is crucial. One approach to address this, is to ensure that several suppliers are capable of producing and delivering materials, as well as quickly upscale their production, for example in case of a natural disaster destroying a factory. A thorough contingency plan is essential in this scenario. This contingency plan is furthermore crucial in the response phase of SCRES, where a simulation model can provide a high knowledge, early in the decision-making process, as illustrated in Figure 11. This leads to better assessment of the contingency plan, and thus a more quick response to SC disturbances. MMS can, due to their flexibility, briefly leverage the recovery aspect, as a continued supply of other products combined with a reconfiguration of the work cells can still yield a high manufacturing system utilization. Furthermore, portfolio external products as suggested by May et al (May *et al.*, 2020), might enable new business opportunities, addressing the growth and renewal phase.

To connect the SCRES with the findings from this dissertation, the general question is “How does MMS contribute to resilience along the SC?” While this in itself is a separate RQ in continuation of this PhD study, some of the findings can be transferred and considered a preliminary study to pursue this RQ. First of all, the different types of flexibility that MMS enable, as identified in section 4.1, provide resilience for the manufacturing facilities in a SC. Especially process and volume flexibility are crucial, naturally in combination with the routing flexibility, to produce products based on availability of sub-components in a starved SC. In this way, the manufacturing facility can continue to manufacture products efficiently, even though component supply and/or demand is low. Another aspect that contributes to SCRES, enabled by the flexibility types of MMS, is production flexibility. As the product and work cell designs proposed in Paper B and C provide guidelines for designing products and work cells they can potentially increase the production flexibility. This type of flexibility has especially contributed to resilience during the recent pandemic, where the ability for example to change products (Malik, Masood and Kousar, 2021), can provide continuous profits for a company that has experienced a major drop in initial products. To reflect, it is though also important to consider the full SC from a holistic perspective. Solely improving resilience in the manufacturing facilities without considering the impact on distribution centers, suppliers, changing demands, etc. would yield unsatisfactory results, unnecessary capital expenditure, and lost opportunities. In order to sufficiently evaluate the proposed RQ, an initial literature review of SCRES, followed by a simulation-based case study, ideally with a case company, would help further investigate how MMS could provide resilience throughout the SC.

5.2 MMS and Sustainability

An important aspect to discuss, is the sustainability impact of MMS. With the increased attention to sustainability, for example with the Sustainable Development Goal (SDG) #9 by United Nations (UN), the manufacturing systems need to address this impact. Rosen and Kishawy present sustainability as the intersection of environmental, economic, and social perspectives (Rosen and Kishawy, 2012). MMS address these perspectives in different ways, especially regarding the SC impact.

The environmental aspect of MMS brings the opportunity to use the flexibility in MMS not only to produce products but also to address the aspects of the 6R methodology. The 6R methodology consists of considerations on how to reduce, recover, redesign, reuse, recycle, and remanufacture (Kuik, Nagalingam and Amer, 2011). MMS can adapt to these components through the flexibility that the manufacturing system facilitates. Due to the redundant work cells, MMS allow for temporarily shutting down work cells in order to minimize energy consumption, thus addressing the "reduce" component of the 6R methodology. This decision on shutting down work cells for energy reductions must actively be implemented in the control system to successfully balance the production targets and the energy consumption. The proposed control system architecture from Paper A can, depending on the actual implementation, account for this. This is heavily based on the deployed energy measurement sensors, as well as the integration with the simulation software. For a discrete-event simulation, Tecnomatix Plant Simulation does, for example, include energy optimization functionalities that can be applied in these scenarios (*EnergyAnalyzer (object)*, no date) and thus directly impact the control system.

To further extend on the sustainability aspect, the energy consumption can be implemented in the reward function of the RL agent in the proposed control system architecture from Paper A to minimize the scope 1 emissions of a company. Current academic references have for example focused on utilizing RL on the heating, ventilation and airconditioning of factories to minimize the scope 1 emissions (Biswas, 2020). While the reward function in the case of balancing throughput and energy consumption would be much more sophisticated, especially also in comparison to the initial investigation case from section 4.3, it does however also add complexity. Practically, the weight for throughput and energy consumption would have to qualitatively be assessed initially, and if static, reviewed continuously, or alternatively implemented as a dynamically changing factor. It is though important to highlight that these weights, or factors, would have to comply with the company strategy and long term approach, especially taking the current scope 1 emissions into account. Additionally, depending on the actual design, implementation and realization, the opportunity of temporarily shutting off work cells to minimize energy consumption is also present. Again, this decision can be an outcome of the proposed control system architecture, taking the production targets, energy consumption targets, etc from the reward function of the RL agent into account. It is important to highlight that this is solely enabled by the flexibility types that MMS facilitate, as identified both Table 3 and Table 1, where especially the volume flexibility is key. To connect this with the overall RO, the opportunity to dynamically alter the manufacturing system to most efficiently meet production and scope 1 emission targets aids the adoption of how to operationalize MMS. This is again only enabled by the flexibility types connected to the manufacturing system paradigm, and practically executed through a sufficient work cell and control system architecture design, such as proposed in Paper B and Paper A, respectively.

Additionally, MMS allow for production of new products in parallel with the reuse, recovering, recycling, and remanufacturing. In this way, returned products can be disassembled in some work cells, depending on the tools they are equipped with. Although this heavily depends on the product and work cell design, the methodologies from Paper B and Paper C account for this, if the company considers it a strategic decision. While this provides a clear environmental potential for the manufacturing system, it does, however, also increase the complexity of the manufacturing control system. Similarly to the energy optimization aspect, it can be included in the simulation model of the control system architecture. Thus the RL agent can account for this and ensure a sufficient prioritization between the manufacturing of new and used products.

It is therefore important to highlight that the flexibility types that is partially enabled by the manufacturing system paradigm itself, as identified in section 4.1, but also the production flexibility that is enabled through the product and work cell design from Paper B and Paper C, is a key enabler for an environmentally sustainable impact from this manufacturing system paradigm. However to also remain economically sustainable, the control system architecture is critical, and in this connection also the sensors and actuators connected to the work cells.

However, the adaption of these components alongside the manufacturing of new products in a MMS also influences the SC. It is crucial that the flow from the consumers to the manufacturing are consistent, accessible, and prioritized by the company as part of their business strategy. While it, under current conditions with semiconductor shortage, can provide an immediate impact, the economic aspect also needs to be addressed in this regard and for MMS as a manufacturing system.

The economic sustainability impact for MMS is important to consider regarding the expected lifetime of the manufacturing system, as well as balancing the investment costs and flexibility aspects. Additionally, the environmental sustainability concerning the SC also induces the need for economic sustainability considerations. While flexibility inevitably results in an increased investment cost of the manufacturing system (Tolio and Valente, 2006), MMS do, due to the concept, induce lower investment costs than other paradigms. This is due to the standardized, reconfigurable work cells that, once the 'prototype' work cell is defined and commissioned, it is a matter of replicating the same cell until a sufficient manufacturing capacity is reached. In this way, the expansion flexibility reduces the economic impact through economies of scale. Economies of scale are furthermore also applicable in the design of the work cell tools, as several tools are needed to create redundancy in the manufacturing system. Although MMS, as a paradigm, might yield lower investment costs than other manufacturing system paradigms that include flexibility, it is unavoidably more expensive compared to a DML.

The expected lifetime of the manufacturing system is also a crucial indicator of economic sustainability. Primarily due to the product and expansion flexibility facilitated by the MMS, the expected lifetime of the manufacturing system is increased. This potentially means that the depreciation time of the manufacturing system is equal to the system components expected functional lifetime. In this way, the fixed manufacturing cost of a product can also potentially be lowered, providing a competitive advantage. Furthermore, the lower cost of introducing new products also economically benefits the lifetime of the manufacturing system.

To extend on the expected lifetime of the manufacturing system in relation to the RQs, the flexibility types that MMS facilitate, with special attention to the product, expansion, and volume flexibility, enable the manufacturing system to dynamically adapt to new product variants (that are designed according to the approach in Paper C) that meet an increasing demand, while the older product variants that are outdated or being replaced are decreasing in demand. This is though also strongly connected to the work cell design that over time might need adjustments, practically implemented as new tools or augmented equipment. In these scenarios, the proposed approaches from Paper B and Paper C are still fully compliant with the given circumstances. Additionally, as new products are introduced and old products are phased out, the control system architecture might require an update to match the current circumstances at the given time. Especially the reward function in the RL agent will need to be dynamic or updated frequently to reflect the strategic prioritization of producing new products versus old products. As new requirements emerge over time, ElMaraghy propose to reconfigure the manufacturing system (a capability MMS facilitate through expansion flexibility), and followed by a virtual mock-up (ElMaraghy, 2005). These considerations are integrated into the control system architecture, where simulation plays a central role.

Finally, the social sustainability is also accounted for in MMS. Where MMS are primarily used for the final assembly of goods (*Danfoss gentænker fabrikken fra blankt papir | Ingeniøren*, no date; Schumacher, Weckenborg and Spengler, 2022), it can yield the opportunity to pursue glocalized manufacturing, moving the final assembly closer to the distribution centers or even the consumers (Chavez and Bilberg, 2014). This is enabled by Manufacturing-as-a-Service (MaaS), where MMS targeted final assembly can be used by several companies, as briefly investigated by Nielsen, da Silva, and Yu (Nielsen, da Silva and Yu, 2020). In this way, the manufacturing company will create a local impact in relation to employment of the local workforce as well as financially contributing to the local society through taxes and by increasing the local wealth and thus purchasing power.

Furthermore, the MMS work cell, proposed in Figure 15, allows for the inclusion of operators with different skills and educations. As the work cell can function both fully automatic as well as collaborative, the operator can select the tasks to perform based on competence level, while the collaborative work cell handles the remaining tasks. As briefly investigated by Greschke et al, Matrix Production increases the working conditions for employees (Greschke *et al.*, 2014). It is though important to highlight that other aspects in the work cell design need to be considered, such as standards like DS/EN 614 that account for ergonomic construction principles of machines (*DS/EN 614-1 + A1:2010*, no date). In this way, as discussed by Greschke et al, also disabled operators with reduced performance can actively contribute to the manufacturing (Greschke *et al.*, 2014), thus increasing the social sustainable impact.

To further relate social sustainability to the RQs, especially the work cell design, as proposed in Paper B, is essential. With the strategic decision prior to the work cell development, it is possible on the second step of the work cell design approach from Paper B, to incorporate measures to assist operators with full or reduced performance. In case this strategic decision is implemented, this does influence the control system, and raises potential ethical concerns, especially when implementing artificial intelligence in the form of reinforcement learning. While the ethical aspect could be integrated as a key performance indicator in the control system (Berrah and Trentesaux, 2021), practically implemented as another factor in the reward function of the RL agent, the quantification of ethics also yields considerations that needs to be thoroughly discussed in connection with the strategic decision. It is however clear that the social sustainability is not an enabler of how to operationalize MMS, but a strategic consideration that can be integrated into the manufacturing system by following the work cell design approach as described in Paper B, as well as in the control system architecture from Paper A. This does however add complexity and ethical concerns, where frameworks on the other hand can contribute to lowering these concerns (Burnett *et al.*, 2022).

5.3 MMS and New Business Opportunities

A strategic opportunity enabled by MMS, and the flexibility connected with it, is MaaS. As suggested by May et al and Nielsen, da Silva and Yu, the opportunity to produce portfolio external products is enabled by MMS (May *et al.*, 2020; Nielsen, da Silva and Yu, 2020). In this way, due to the flexibility in MMS, local manufacturers can benefit from the manufacturing system and still enable a high OEE, for example during seasonal fluctuations in demand. In other words, it allows the company to both sell their products but also sell available manufacturing capacity and manufacturing design expertise to the local companies. By selling the manufacturing capacity, the company can also yield environmental, economic, and social sustainability. The environmental sustainability accounts for a lower local need for manufacturing equipment thus ensuring a higher OEE of the local manufacturing facilities. The economic sustainability is addressed by the higher utilization for the company, while the local companies buying the MaaS do not require huge investments in manufacturing equipment. Finally, the social sustainability impacts the employees as it ensures a high local workforce employment, especially in case of seasonal demand deviations.

To further elaborate on topic of MaaS, also known as Service Manufacturing (Kusiak, 2020), and in that connection how MMS allow the opportunity to sell available manufacturing capacity, it is essential to discuss how the flexibility types that MMS facilitate can support this, also in relation to the product and work cell designs for a MMS. While it, as described in section 5.2, is an opportunity to shutdown individual work cells to minimize the energy consumption, while still meeting production targets, it can be alternatively approached as an opportunity to produce portfolio external products. Especially the product flexibility that MMS facilitate is essential for this capability combined with the volume flexibility. It does however require that the initial product design can be modified to sufficiently be integrated into the existing work cell design. This does indeed bring certain limitations in terms of identifying potential portfolio external products. On the other hand for the products where this is a viable solution, it adds great amounts of resilience to the portfolio external products supply chain, especially considering a dual-sourcing approach. Again, to discuss how this relates to the operationalization of MMS, the control system architecture is essential. The available manufacturing capacity that can be sold has to be prioritized in the control system, however the importance (or relational factor to producing the portfolio internal products) needs to be qualitatively assessed in relation to the company strategy.

Another business opportunity for MMS is the concept of a supply and purchasing cooperative, as typically realized in the agricultural sector (Altman, 2010). By establishing production sites following this type of cooperative, the local small and medium-sized enterprises can minimize the investment costs of developing and maintaining a production, thus essentially achieve the benefits of economies of scale. Additionally, they can focus on the product design, thus freeing resources to further expand the product families or optimizing the product design. In this type of cooperative, the need for maintenance personel and operators are needed, as well as experts in product design for MMS, due to the cooperative typically being run as a traditional company (Altman, 2010). In this way, the local small and medium-sized enterprises can share these expenses that overall are lower, compared to individually owning and operating manufacturing capabilities.

It is clear that the opportunity of a supply and purchasing cooperative is solely enabled by the flexibility types that a MMS facilitate, where especially the production, expansion, and product flexibility are enabling factors. For such a cooperative to be operationalized following the MMS paradigm, the work cell and product designs are though essential. The approaches from Paper B and Paper C are therefore a central part of operationalizing MMS, not only for a non-cooperative approach, but even more importantly for a cooperative approach. Where the Design for MMS take into account the different product families, this aspect is even more essential for the cooperative approach, as the different product families might differ drastically, depending on the products that the small and medium-sized enterprises connected to the cooperative provide. In this connection, the control system architecture is also an important factor to operationalize a MMS for a cooperative approach. To efficiently balance several stakeholders and their interests, production targets, costs, etc. the reward function for the RL agent would for example need to be frequently adjustable to ensure a mutually satisfactory performance for the manufacturing of the different goods.

To address the increased SC complexity from this approach, it is important to consider whether the MMS cooperative should solely focus on the final assembly of products, or technologies such as additive manufacturing can be applied to lower the SC complexity by locally manufacturing components.

5.4 MMS and the Red or Blue Pill

To conclude the discussion, MMS will be evaluated as a potential manufacturing system of the future. When the manufacturing companies are designing new production sites, they have to make the choice between adapting the current solutions with the risk of not meeting the future demands for a manufacturing system, or adopt a new manufacturing system paradigm, such as MMS. This choice is similar to when the character Morpheus offers the character Neo the choice between a red or blue pill in the movie "The Matrix" from 1999 (Wachowski and Wachowski, 1999). It is though important to highlight that, in contrast to Neo, not all manufacturing companies benefit from 'taking the red pill'. To better address what manufacturing companies that would benefit from this manufacturing system paradigm, it is essential to highlight the expectations to the challenges and capabilities for the future manufacturing system. These can be seen in Figure 21, adapted from Fries et al (Fries *et al.*, 2021).

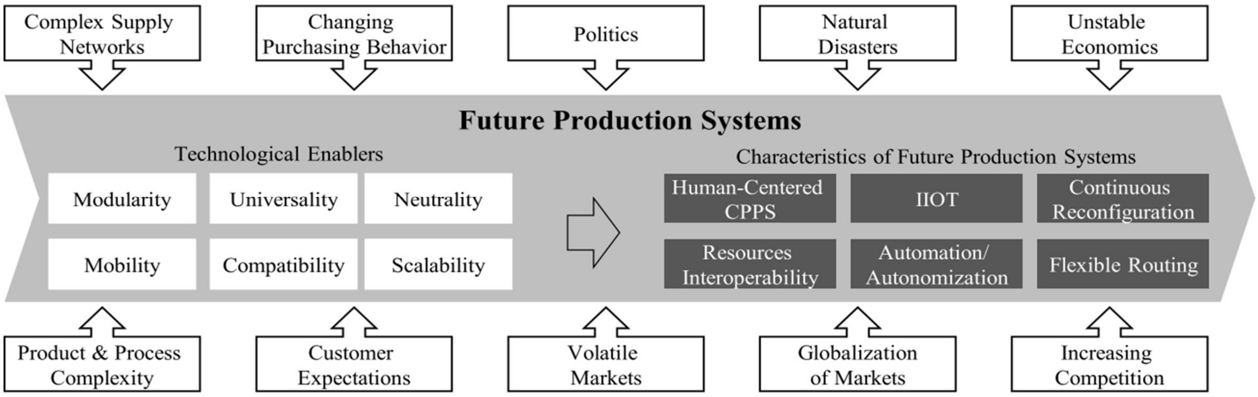

Figure 21 Challenges, Characteristics, and Enablers of Manufacturing Systems of the Future, adapted from(Fries et al., 2021)

Some of the challenges that MMS, due to the facilitated flexibility, can address, is the volatile markets that results in changing purchasing behavior, globalization of markets, and product and process complexity. Especially the volatility, MMS can quickly adjust to, due to the volume flexibility and product flexibility. By cost-efficiently up or downscaling the production, while introducing new products, the manufacturing system is suitable for markets that phase the risk of a changing purchasing behavior. It is though, as discussed earlier, very dependent on the SC and the SCRES.

The challenge of product and process complexity is also addressed by MMS, as the two proposed approaches on designing the work cells and products address this challenge. It is though clear that MMS are not a preferable solution where minimizing manufacturing area or volume is a high priority. This means that process complex products like semiconductors, produced in a clean room, or products that require cold environments, are out of scope. Due to flexible routing, typically enabled by AGVs or AMRs, this increases the manufacturing floor area, which is unpreferable under these circumstances, due to the increased cost. As this dissertation primarily has investigated unit assembly of electronic products, this serves as the baseline for this conclusion, although further research in the machining or process industry is needed. As discussed in the previous subsections, this manufacturing system can be an essential actor as a local assembly factory in the globalized manufacturing scene.

Based on the discussion, it can be concluded that MMS possess crucial aspects for the factory of the future. From Figure 21, MMS address the continuous reconfiguration, flexible routing, automation, and resources interoperability, hence it can – under the discussed circumstances – be considered a manufacturing system of the future. It is clear that the manufacturing companies that do not face these challenges, will not benefit drastically from implementing the MMS paradigm. Other parameters might though, still tempt these manufacturing companies. Especially in regards to the sustainability and SCRES, MMS benefit from the facilitated flexibility. In this way, the manufacturing system is sufficiently resilient towards future disruptions, while efficiently balancing current and future product variety and production volumes. These benefits, combined with the potential business opportunities that arise with MMS can function as an enabler for adopting this manufacturing system paradigm. It therefore can be considered a manufacturing system of the future for manufacturing companies that face the challenges of volatile markets, changing purchasing behaviour, globalization, and product as well as process complexity.

To connect this perspective with the empirical work presented in this dissertation, it is clear that the challenges as highlighted in Figure 21, and especially the challenges on increasing competition, volatile markets, and product and process complexity has served as inspiration for the development of the work cell from the laboratory case study. The work cell from the company case study has been designed with the perspective of accepting a higher product complexity, by focusing on aspects like product flexibility. In practice, the possibility of selecting either a collaborative setup or a fully automated setup enables the opportunity to mitigate product complexity when this is needed. Furthermore, the volatile markets is also addressed in the work cell, as the operator on top of the product flexibility also enables volume flexibility, under the condition that operators are not present during all shifts.

When considering the technological enablers, this dissertation has contributed by exemplifying aspects to enable modularity and scalability. While this is a fundamental aspect from the manufacturing system paradigm of MMS, the work cell design approach as well as the product design approach enables practitioners to convert these abstract enablers into tangible assets. This is also linked to the characteristics of future production systems from Figure 21, where this dissertation has paved the way for realizing continuous reconfiguration and resources interoperability through the proposed control system architecture from Paper A. This key contribution of the dissertation has enabled practitioners to enable the benefits of MMS, and thus these beforementioned aspects, without compromising flexibility and performance. Furthermore, the designed work cell and approach to design these, encourage human-centered cyberphysical production systems, for example through considering the level of automation needed for a given work cell under design. All in all, it can be concluded that the key contributions of this dissertation and empirical work has further advanced the current literature in a positive direction to consider MMS a manufacturing system of the future.

5.5 Research Design and Methodology

An important aspect to discuss and reflect on is the research design and methodology. This section will discuss primarily the methodologies with special attention to case studies. Furthermore, the topic of triangulation is discussed and reflected upon.

Since the PhD study include industrial case studies, it is important to evaluate whether an action research approach or an interactive research approach is suitable. Where the joint learning serves as the central aspect of interactive research (Ellström and Brulin, 2007), action research is focused on the applied knowledge in an existing organization that solves a practical problem (Shani and Coghlan, 2021). While there are indeed similarities between those two research approaches, there are also certain disadvantages connected with action research that interactive research is addressing. First of all, the strong involvement in the organization will enhance the risk of bias and an objective critical analysis (Ellström and Brulin, 2007). Furthermore, Ellström and Brulin argue that the focus on a single organization complicates the process of generalizing the analysis, as well as the focus is typically centered around the practical knowledge and contribution and less on the theoretical (Ellström and Brulin, 2007). While some of these challenges can be addressed through sufficient triangulation, as discussed in the paragraph below, an interactive research approach would detach the researcher from the practical contributions. This does not only have a positive effect on the research bias, but also allows the researcher to focus on the holistic perspective of the theoretical contribution.

In relation to the research design of RQ2 and RQ3, an interactive research approach would have addressed some of the weaknesses connected with the performed case studies. First of all, the strong focus on the practical development aspects of especially the laboratory case study, but also partially the company case study of RQ3, compared to the theoretical aspects would have been drastically changed. The current approach of action research has resulted in less time to for example qualitatively evaluate the performance of MMS compared to other manufacturing system paradigms. Here, an interactive research approach would have enabled the PhD candidate to critically analyze the performance in relation to other paradigms at a more holistic perspective. While this also would have positively impacted the research outcome, especially in terms of the control system architecture and thus RQ3, this interactive research approach does also have limitations. First of all, the opportunity of partly identifying and partly contributing to a case study following an interactive research approach, taking the limited time period of a PhD study into account. To connect this to the empirical work of the PhD dissertation, an interactive research approach for RQ3 would require the participating case company to not yet have initiated the control system development, as "*The ambition in interactive research is to conduct research with the participants during the entire research process – from the definition of the problem to the dissemination of results*" (Ellström and Brulin, 2007). In case the participants have already started developing solutions, they pose a higher risk of bias both in terms of practical development, as well as theoretical contribution. In other words, the interactive research approach would have provided a stronger theoretical contribution in connection to RQ3 and the key findings, and with the results that are more generally applicable. However, due to the limited window of time to initialize such as project, the action research approach was deemed appropriate, although this has presented certain weaknesses. To further elaborate on the weakness of the action research approach and the more limited theoretical contrubtion, an alternative approach to the interactive approach of RQ3 would be to design the research to follow a more descriptive, fundamental, and quantitative approach. This would drastically increase the theoretical aspect as the data source would rely more on academic literature, and the methodology would be of a more literature research nature. On the other hand, this more theoretical focus pose the risk of minimizing the practical applicability, and thus does not fully support the overall RO. Finally, it is important to highlight that an interactive research approach would not be feasible for the laboratory case study in RQ2, due to the limited number of participants and researchers in that case study. Here, the action research approach poses a sole opportunity to perform practical experiments. In this case, triangulation is essential.

Triangulation plays a central role in ensuring valid and high-quality results in academia. Bans-Akutey and Tiimub summarize six types of triangulation: 1) methodical triangulation, 2) data triangulation, 3) investigator triangulation, 4) theoretical triangulation, 5) environmental triangulation, and finally 6) multiple triangulation (Bans-Akutey and Tiimub, 2021). It is essential to discuss these types of triangulation in relation to the research design of each RQ. For RQ1, triangulation of the results to increase the credibility of the results would be performed as a multiple triangulation, where methodical triangulation and investigator triangulation is applied. The methodical triangulation would in addition to the SLR, also apply a more analytical approach and further extend the findings from Table 1 by additional SLR. Based on a more solid data foundation, a comparative, qualitative study will be performed, where ideally industrial implementations are also assessed to further strengthen the credibility of the research findings from RQ1. In addition to the methodical triangulation, an investigator triangulation could be applied. By having the research outcome verified and validated by subject-matter experts, identified through key contributors within the field of MMS, the credibility of the results would be further enhanced. Due to the limited amount of contributions to the field of MMS, a qualitative approach following structured interviews will be applied. A quantitative survey would indeed also highlight these findings, however the limited amount of potential candidates at the cost of missing details that a quantitative study per se deduce, this approach will be applied at a later stage, when the pool of participants within the field of MMS has drastically increased.

For RQ2, a multiple triangulation approach could be applied, where an environmental and investigator triangulation would greatly improve the credibility of the results. For the product design approach, as described in Paper C, an environmental triangulation, where the proposed approach is applied on products in a different environmental setting, would provide great insights into the credibility of the proposed approach. Ideally, to provide the highest levels of credibility, this type of triangulation would be applied in a multitude of cases with varying products and product families. This quantitative consideration could be performed using multiple focus group interviews in a laboratory setting with randomized products. While this type of triangulation would reduce the amount of bias, compared to qualitatively interviewing company stakeholders, it would also provide more questionable results, due to the limited prior knowledge of design considerations and manufacturing processes the focus group interviewees would have. In other words, it is essential to select focus group interviewees that would have sufficient prior subject matter knowledge on the products, to provide viable discussions and results. Alternatively, the qualitative approach of interviewing company stakeholders would reduce this complexity, however introduce the risk of bias that needs to be critically analyzed and accounted for, in order to sufficiently verify and validate the research outcome of the RQ. One approach that would strengthen the credibility of the research outcome, would be to follow an interactive research approach on a new product development project in a case company. This does increase the qualitative research design and allow for continuous feedback, access to subject-matter experts, etc. The access to subject-matter experts would also be a crucial part of the investigator triangulation that in this case solely would be of a qualitative nature, realized through either structured interviews, or more frequent open-ended interviews. Similar triangulation approach will be applied on the work cell design, where ideally a new product development case can be used in an interactive research approach to triangulate the proposed design approach. Investigator triangulation through qualitative interviews with subject-matter experts would also be preferred to further strengthen the credibility of this approach.

For RQ3, the triangulation will ideally be performed as an environmental triangulation combined with an investigator triangulation. This multiple triangulation approach would partially increase credibility of the results by introducing experiments that can both verify and validate the performance of the proposed control system architecture, but also – ideally – provide insights on how the proposed control system architecture would perform in comparison with existing control system architectures. The environmental triangulation would therefore be performed as an interactive research approach, where a control system would be designed for a MMS. While this type of triangulation pose challenges, as discussed below, it is important to further combine it with other types, such as investigator triangulation. Investigator triangulation in this case could be performed by qualitatively interviewing subject-matter experts within partially MMS and partially control system architectures. There is to the knowledge of the PhD candidate, no single subject-matter expert that pose the interdisciplinary knowledge without being involved actively or passively in the study in the first place. As the two fields are not directly related, the methodology for triangulating is crucial. A quantitative approach might yield survey responses that differ drastically between the two groups of subject-matter experts, leaving the triangulation results questionable and thus not strengthens the credibility of the research result. A qualitative approach is therefore preferred, where open-ended interviews can be applied to sufficiently triangulate the research finding, while still accounting for the knowledge of the expert.

A major disadvantage of these types of triangulation is however the resource consumption, in terms of time, finances, and energy (Bans-Akutey and Tiimub, 2021). Especially the time and financial resources are strictly limited throughout a PhD study, and that naturally pose limitations to the types of triangulation that can be applied. In the above paragraphs, ideal cases have been discussed, however, realistically in this PhD study, it will primarily be investigator triangulation that will be applied, due to the more limited financial cost of this approach. A major advantage of the case studies is though the access to subject-matter experts that can provide such triangulation on the results. This means that the triangulation typically is performed as an iterative, unstructured approach, where continuous reflection, verification, and validation is performed. This has been a central part of the full PhD study, and especially concerning the RQs and RO. The subject-matter experts have been qualitatively selected based on the RQ and the type of feedback that has been needed at the given time.

6. Conclusion

This final section of the kappa summarizes the individual RQs and the RO. Furthermore, the theoretical and managerial contributions are stated together with the limitations of the research performed. Finally, the future works are presented to inspire as well as enable researchers to further enhance the research and findings within this field and topic.

The initial RQ, investigating how MMS facilitate flexibility, is answered using a SLR as presented in Paper D and further extended in section 4.1. Based on this foundation, it can be concluded that the current literature support that MMS especially facilitate material handling, routing, operation, and control program flexibility. The remaining six types of flexibility are not as thoroughly presented in literature, although they still are of significant importance in relation to how MMS facilitate flexibility. In section 4.1, it is analyzed how material handling, routing, process, operation, volume, product, expansion and production flexibility is facilitated through the manufacturing system paradigm and its core definition (as presented in section 2.2). It can be concluded that these types of flexibility are facilitated through the reconfigurability and standardization of the work cells, and its design approach as proposed in Paper B, as well as the need for flexible intralogistics. The remaining types of flexibility can be enabled through the technical implementations and realizations, however this requires that it is actively pursued, and does not come integrated in selecting the manufacturing system paradigm. It is though strongly encouraged to fully leverage the benefits of MMS.

The second RQ, addressing how to design MMS, is answered using a laboratory case study and a company case study. As the current literature has primarily addressed the design of MMS on a manufacturing system level, the two case studies have focused on the work cell design approach and the product design approach. These theoretical contributions are essential as the performance of the manufacturing system is heavily linked to the performance of the work cells. The laboratory case study have therefore served as the foundation for investigating the practical considerations of work cell design prior to the company case study, as well as enabled the product design approach to be developed. The company case study has served as the foundation for the methodological approach to design work cells for MMS. It can therefore be concluded that to design MMS, the work cell and product design are symbiotically connected, and needs to be considered to ensure that the designed manufacturing system both enable the high degrees of flexibility in an efficient manner. The current approaches to designing products and work cells does not fully leverage these aspects. The design of MMS on a manufacturing system level is already considered in literature and partially addressed in the theoretical background.

The third RQ, addressing the control of MMS, is answered using a company case study. The key aspect of the case study is the development of a control system architecture designed for MMS. Through the use of for example RL and simulation, it is possible to efficiently control a MMS thus leveraging the flexibility of the manufacturing system compared to the use of existing control system architectures. The proposed control system architecture explains the interaction on three abstraction levels and how the different parts of the control system architecture interact with partly external software systems and partly the internal components. As the case study and Paper A also presents, control of MMS has currently only been addressed in relation to AGV control algorithms, and no overall control system architecture has been proposed. The key contribution of the case study, and Paper A, is therefore an overall control system architecture dedicated to MMS that accounts for the flexibility types that MMS facilitate and leverage the performance of this manufacturing system.

Addressing the RO, this dissertation expands the current literature on transitioning from the design of MMS as a manufacturing system by investigating how to efficiently design both the work cells and the products to be produced therein. As the manufacturing system and the work cells enable high degrees of flexibility, it is essential to develop a dedicated control system architecture to benefit from this increased flexibility. As this is considered operationalizing MMS, it is crucial to also address the broader perspective that this manufacturing system enables. First of all, the flexibility on the manufacturing system level requires a resilient SC that sufficiently can leverage this flexibility. Secondly, MMS also enable a strong sustainability impact, partially due to the SCRES, partially due to the flexibility that the manufacturing system facilitates. The SCRES and sustainability aspects finally enables the companies implementing this manufacturing system to pursue new business opportunities.

The dissertation has four clear theoretical contributions. The first theoretical contribution is the product design approach, presented in Paper C. The design approach helps the decision-maker in optimizing the product design throughout the product families such that it optimizes the manufacturing in a MMS work cell. The second theoretical contribution addresses the MMS work cell design. As the performance of the manufacturing system is heavily dependent on the performance of the work cells, the design approach presented in Paper B maximizes the performance of these work cells. The third theoretical contribution addresses the control system of MMS by proposing an architecture that leverages the performance of the overall manufacturing system. This is presented in Paper A. The final yet unpublished theoretical contribution is the outcome of the systematic literature review. By identifying the facilitating flexibility types of MMS, it is furthermore possible to distinguish MMS as a paradigm from the remaining manufacturing system paradigms, as identified in partly the theoretical background and partly section 4.1.

The managerial contributions of the dissertation is centered around the flexibility types and their aspects of MMS. This is strongly connected with the fourth theoretical contribution. Essentially, the kappa highlights that MMS enable high levels and a multitude of flexibility, while providing the foundation for a high production throughput. This means that the manufacturing system is capable of providing a HMHV production. This does not only imply a high resilience but also, due to the design, a high redundancy. Similarly, the scalability aspects of MMS are crucial for adapting to the current manufacturing trends. Furthermore, MMS are gaining an increasing attention, where global companies like Audi, Danfoss Drives A/S, and KUKA all implemented MMS. However, the managerial contributions of this dissertation is to increase and facilitate the adoption of MMS for other companies as well to benefit from the flexibility that MMS facilitates. Finally, by implementing and following the first three theoretical contributions, the decision-makers are assisted in transitioning from the design phase to the control phase, thus operationalizing MMS as a manufacturing system paradigm.

The kappa does though have some limitations. First of all, in the theoretical background, Table 1 is generated based on the manufacturing system paradigms (with the addition of MMS) and the 10 types of flexibility, identified by ElMaraghy (ElMaraghy, 2005). Based on the current literature, the different manufacturing system paradigms are evaluated in respect to each type of flexibility to address how they differ. The current literature does though not sufficiently address each type of flexibility, as summarized by ElMaraghy, for each manufacturing system paradigm. This is a clear limitation of the findings. The evaluation of the different types of flexibility for the manufacturing system paradigms that are not addressed in literature is assessed based on the available current literature and the descriptions of the manufacturing system paradigms therein. It is though crucial to highlight that in actual, specific implementations of the manufacturing system paradigms, deviations from Table 1 can occur. To address this limitation, SLRs for each paradigm would strengthen this claimed degrees of flexibility from Table 1. Although this is out of scope for this dissertation, it poses a future research opportunity.

A second limitation to this dissertation is the company case studies. Ideally, a multitude of companies would have been investigated to broaden the data foundation. As MMS are a more recent manufacturing system paradigm, limited implementations are available, and thus not accessible during the PhD project period. While simulation models to some degree can address this limitation, they tend to be simplifications of reality and thus not sufficiently address the actual manufacturing challenges. Triangulation is discussed in detail in section 5.5.

While this kappa has provided answers to the research questions and hence expanded the current literature and knowledge within this field, it has also paved the way for future works to investigate. These future works address several limitations of the answers to the research questions as well as personal interests and especially reflections of the PhD student.

A crucial aspect to further investigate is the impact of focused flexibility in MMS. While a fully standardized, reconfigurable work cell can be considered an optimal solution, the actual implementation costs are to be compared with the need for flexibility. Here, focused flexibility might yield more applicable results, especially in scenarios with expensive or cumbersome manufacturing equipment.

Another aspect to further investigate is the impact of human operators, especially in relation to flexibility. Briefly elaborated on during the work cell development in the laboratory case study, operators are a crucial resource in a manufacturing system that require flexibility. With the recent trends within human-centric solutions and human-machine interfaces, operators might play a central role in the factory of the future and MMS.

An additional aspect to consider is the impact on the supply chain. Adopting MMS and the flexibility it enables, also yields a pressure on the supply chain to efficiently supply raw materials and distribute it after processing. While MMS inevitably increase the supply chain resilience in a single link, the impact on the full supply chain is to be determined in future studies.

An aspect to consider for future works is the possibility of remanufacturing, recycling, reuse, and similar concepts alongside the normal manufacturing in a MMS. As MMS enables a high operation flexibility, this opportunity might leverage the adoption of the manufacturing system. The sustainability impact of MMS, both from an economic but also environmental perspective is of interest for future works.

A final aspect to consider for future works is the use of MMS in a MaaS perspective. Although briefly suggested by Nielsen, da Silva, and Yu (Nielsen, da Silva and Yu, 2020), the impact of a manufacturing system as a supply and purchasing cooperative for local small and medium-sized enterprises is worth considering for boosting entrepreneurship in mechatronic products. The impact on the supply chain, glocalized production, and remanufacturing and repairing in these cooperative productions, with MMS as an enabler, is of future consideration as well.

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Appendix

Paper List

This introductory subsection marks the end of the Kappa, and the beginning of the Appendix. The Appendix contains the publications that the PhD student has authored and co-authored throughout the PhD study, related to the dissertation. In Table 4, the publications are presented. Furthermore, co-author statements can be found attached in the same order for each paper after the full papers.

Paper	Title	Authorship	Journal/Conference/Book	Year	Status
A	Control System Architecture for Matrix-Structured Manufacturing Systems	Main	Computers in Industry	2023	Published
B	Work Cell Design for Matrix-Structured Manufacturing Systems	Main	International Journal of Interactive Design and Manufacturing	2022	Under Review
C	Product Design for Matrix-Structured Manufacturing Systems	Main	CIRP Design/ Procedia CIRP	2022	Published
D	Matrix-Structured Manufacturing Systems and Flexibility – A Systematic Literature Review	Main	CIRP CMS/ Procedia CIRP	2023	Under Review

Table 4 Publications

Paper A

Paper B

Paper C

Paper D

Co-Author Statements