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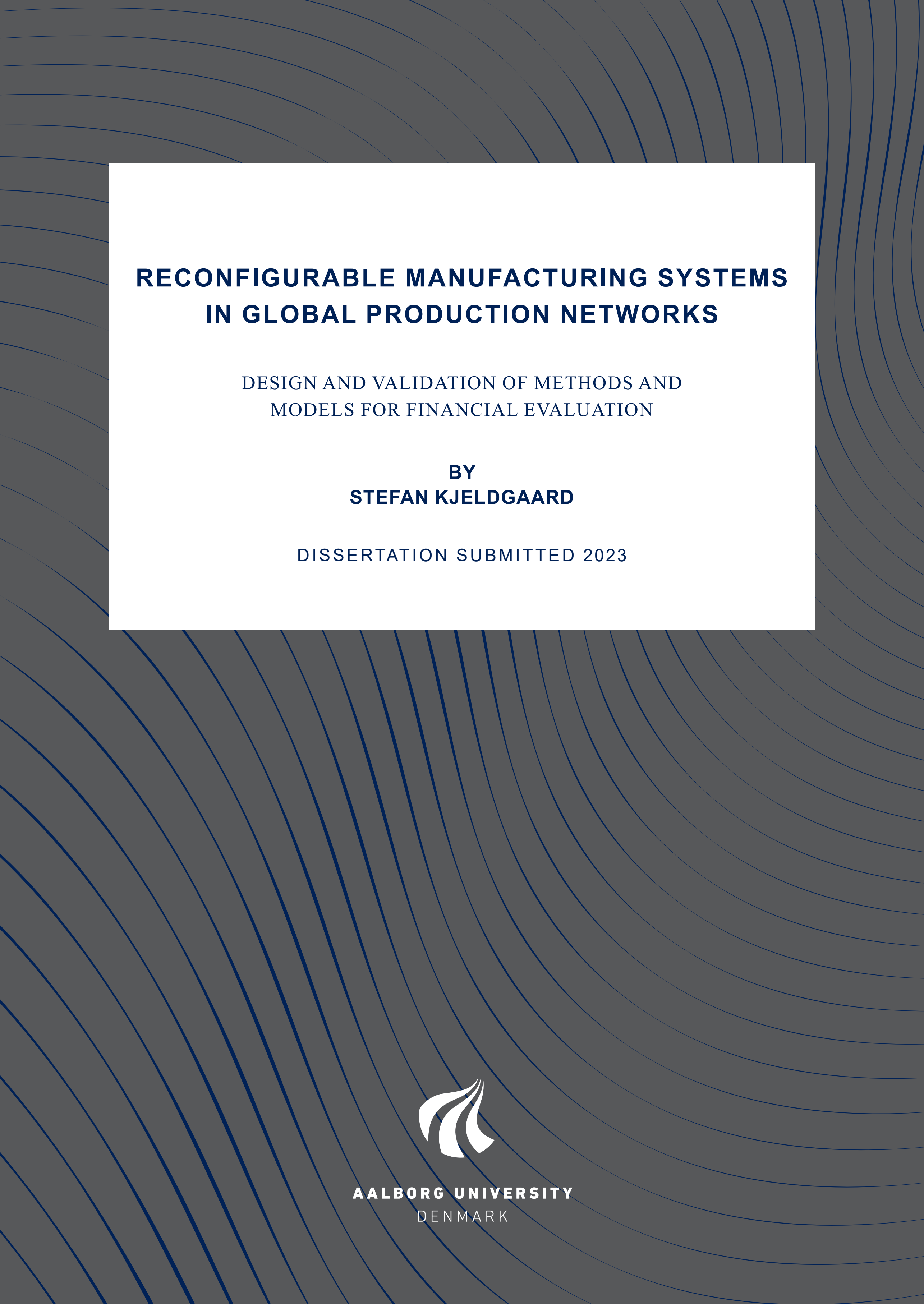

RECONFIGURABLE MANUFACTURING SYSTEMS IN GLOBAL PRODUCTION NETWORKS

DESIGN AND VALIDATION OF METHODS AND MODELS FOR FINANCIAL EVALUATION

BY
STEFAN KJELDGAARD

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

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CV

Stefan Kjeldgaard was born in Viborg, Denmark. He studied at Aalborg University, where he completed a BSc degree in Global Business Engineering in 2018, followed by a MSc degree in Operations and Supply Chain Management in 2020. Since then, he has worked on his PhD at the Department of Materials and Production at Aalborg University in collaboration with Vestas Wind Systems A/S. His research is part of the Manufacturing Academy of Denmark, funded by the Innovation Fund Denmark.

ENGLISH SUMMARY

This PhD dissertation is the result of a three-year research project at the Department of Materials and Production at Aalborg University in close collaboration with Vestas Wind Systems A/S. The project is motivated by an industrial need and research deficit of methods and models for the financial evaluation of reconfigurable manufacturing systems in global production networks.

The research project aims to support decision-making to advance a paradigm shift in the production domain that can enable efficient adaptability and resilience to uncertain changes. These capabilities are needed to secure a competitive advantage in the global wind energy industry. The fierce competition amongst firms increases the introduction rate of larger wind turbines for the onshore and offshore markets. Like the markets, the production is global across multiple factories and countries. Supply disruptions, transportation restrictions, and localization requirements pressure the firms to produce near the demand. However, the demand fluctuates on variety, volume, timing, and location, requiring the production mix of the factories to be adapted accordingly. This imposes frequent reinvestments in capital-intensive assets, which is further intensified when using dedicated manufacturing systems.

The main contribution of the research project is a method and model for the financial evaluation of reconfigurable manufacturing systems in global production networks. The method supports the evaluation of manufacturing systems where reconfigurability is suitable to accommodate new product introductions based on the potential to reduce reinvestment costs. The model supports the calculation of the impact of reconfigurable designs, which includes the investment, reconfiguration, production, inventory, and transportation costs. In brief the method supports to answer which systems are suitable to be reconfigurable? The model supports to answer what are the monetary benefits?

The contributions are validated through industrial application. The results indicate monetary savings of forty to ninety-five million euros per wind turbine blade family over half a decade. The monetary savings are enabled by an efficient, adaptable, and resilient global production network of blade factories with reconfigurable blade molds. The results motivated the decision to patent and implement the design.

From a theoretical perspective, the contribution is a set of works that interconnects the research areas: financial evaluation, reconfigurable manufacturing systems, and global production networks. From an industrial perspective, the contribution can motivate global manufacturing firms to advance the development of reconfigurable manufacturing systems.

DANSK RESUME

Denne PhD afhandling er resultatet af et treårigt forskningsprojekt ved Institut for Materialer og Produktion på Aalborg Universitet i tæt samarbejde med Vestas Wind Systems A/S. Projektet er motiveret af et industrielt- og forskningsmæssigt behov for metoder og modeller til økonomisk evaluering af rekonfigurbare produktionssystemer i globale produktionsnetværker.

Forskningsindsatsen har til hensigt at understøtte beslutningstagen for at fremme et paradigmeskift i produktionsdomænet der kan medføre kosteffektiv tilpasningsevne og modstandsdygtighed overfor uforudsigelige ændringer. Disse kapabiliteter er især nødvendige for at sikre en konkurrencemæssig fordel i den globale vindmølleindustri. Virksomhederne indgår i hård konkurrence der medfører en stigende introduktionsrate af større vindmøller på markeder til både land og hav. Ligesom markederne, så er produktionen global på tværs af adskillige fabrikker og lande. Forsyningsforstyrrelser, transportrestriktioner samt lokaliseringskrav presser virksomhederne til at producere nær efterspørgslen. Efterspørgslen varierer dog i forhold til varietet, volumen, timing, og lokation som kræver at fabrikkernes produktionsmiks tilpasses i overensstemmelse hermed. Aftrækket heraf medfører hyppige geninvesteringer af omkostningstunge aktiver, hvilket ydermere intensiveres ved brug af dedikerede produktionsapparater.

Forskningsprojektets hovedbidrag er henholdsvis en metode og model til økonomisk evaluering af rekonfigurerbare produktionssystemer i globale produktionsnetværker. Metoden understøtter identifikation af produktionssystemer hvor rekonfigurerbarhed er velegnet til at imødekomme nye produktintroduktioner baseret på potentialet for at nedsætte geninvesteringsomkostningerne. Modellen understøtter beregningen af rekonfigurerbare designs omkostningspåvirkning, hvilket inkluderer investerings-, omstillings-, produktions-, lager-, og transportomkostninger. Kort sagt, så er metoden og modellen henholdsvist målrettet besvarelsen af hvilket system der giver mening at lave rekonfigurbart og hvad et efterfølgende design medfører af økonomiske gevinst.

Forskningsbidraget er valideret gennem industriel anvendelse. Resultaterne indikerer en besparelse på en halv milliard danske kroner per vindmøllevingestøbeformsfamilie over et halvt årti. En besparelse der muliggøres af et tilpasnings- og modstandsdygtigt globalt produktionsnetværk af vingefabrikker med rekonfigurbare vingestøbeforme. Resultaterne har motiveret beslutningen om at patentere og implementere designet.

Fra et teoretisk perspektiv, så er bidraget en række værker der sammenkobler dele fra forskningsområderne i økonomisk evaluering, rekonfigurerbare produktionssystemer og globale produktionsnetværker. Fra et industrielt perspektiv, så er bidraget en række værker der kan motivere globale produktionsvirksomheder til at fremme udviklingen af rekonfigurerbare produktionssystemer.

ACKNOWLEDGMENTS

I never believed I would complete a PhD project. I never even intended for university. Somehow, I find myself in this position. It required hard work, some luck, and, most of all, support from the people around me. I could not have done it without them.

Firstly, I would like to thank my three supervisors, *Thomas Ditlev Brunø*, *Ann-Louise Andersen*, and *Kjeld Nielsen*. Without your support, advice, and guidance, I could not have managed the project. *Ann-Louise*, thank you for your encouragement to continue the PhD when I lacked belief. *Thomas* and *Ann-Louise*, thank you for forcing me to take a break when the pressure overwhelmed me. I would also like to thank *Rasmus Andersen* and *Alessia Napoleone* for the discussions and advice. A special thanks to my colleagues from *Jönköping, Sweeden*. *Carin Rösiö*, thank you for the opportunity to visit. *Simon Boldt* and *Filip Skärin,* thank you for our collaboration and friendship.

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Viborg, November 2023

Stefan Kjeldgaard

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LIST OF ABBREVIATIONS

AEP	Annual Energy Production
DMS	Dedicated Manufacturing System
DSR	Design Science Research
FMS	Flexible Manufacturing System
GPN	Global Production Network
IP	Integer Programming
LCC	Life Cycle Cost
LCoE	Levelized Cost of Energy
LME	Large Manufacturing Enterprise
LP	Linear Programming
MADE	Manufacturing Academy of Denmark
MIP	Mixed Integer Programming
MSA	Manufacturing System Alternative
NPI	New Product Introduction
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OM	Operations Management
PLC	Product Life Cycle
RMS	Reconfigurable Manufacturing System
SME	Small and Medium-sized Enterprise
TNC	Total Network Cost

LIST OF PAPERS

A. Kjeldgaard, S., Napoleone, A., Andersen, A-L., Brunoe, T. D., & Nielsen, K. (2021). Changeable Manufacturing: A Comparative Study of Requirements and Potentials in Two Industrial Cases. In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems* (pp. 452-461). IFIP Advances in Information and Communication Technology, 631. Springer, Cham. https://doi.org/10.1007/978-3-030-85902-2_48

B. Kjeldgaard, S., Andersen, R., Napoleone, A., Brunoe, T. D., & Andersen, A-L. (2023). Facilitating Manufacturing System Development: Mapping Changeability Capabilities in Two Industrial Cases. In *Advances in System-Integrated Intelligence* (pp. 626-635). Lecture Notes in Networks and Systems, 546. Springer, Cham. https://doi.org/10.1007/978-3-031-16281-7_59

C. Kjeldgaard, S., Andersen, A-L., Brunoe, T. D., & Nielsen, K. Evaluation of reconfigurability potentials in a global production network. (Under review by the CIRP Journal of Manufacturing Science and Technology, submitted November 2023).

D. Kjeldgaard, S., Brunoe, T. D., Andersen, R., Sorensen, D. G. H., Andersen, A-L., & Nielsen, K. (2022). Brownfield Design of Reconfigurable Manufacturing Architectures: An Application of a Modified MFD to the Capital Goods Industry. *Procedia CIRP*, *107*, 1293-1298. https://doi.org/10.1016/j.procir.2022.05.147

E. Kjeldgaard, S., Jorsal, A. L., Albrecht, V., Andersen, A-L., Brunoe, T. D., & Nielsen, K. (2021). Towards a model for evaluating the investment of reconfigurable and platform-based manufacturing concepts considering footprint adaptability. *Procedia CIRP*, *104*, 553-558. https://doi.org/10.1016/j.procir.2021.11.093

F. Kjeldgaard, S., Andersen, A-L., Brunoe, T. D., & Nielsen, K. (2022). Methods and Models to Evaluate the Investment of Reconfigurable Manufacturing Systems: Literature Review and Research Directions. In *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems* (138-146). Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-90700-6_15

G. Kjeldgaard, S., Andersen, A-L., & Brunoe, T. D. (2023). Enabling adaptability and resilience of a global production network: A model to evaluate capital and operational expenses of reconfigurable production systems. *Journal of Manufacturing Systems*, *66*, 142-162. https://doi.org/10.1016/j.jmsy.2022.12.003

In addition to the main papers of the dissertation enumerated above, a set of smaller contributions have been made in the following books, papers, and videos.

H. Andersen, A-L., Andersen, R., Napoleone, A., Brunø, T. D., Kjeldgaard, S., Nielsen, K., Sorensen, D. G. H., Raza, M., Bilberg, A., Rösiö, C., Boldt, S., & Skärin, F. (2022). *Nye veje til omstillingsparat og rekonfigurerbar produktion: Grundprincipper, fremgangsmåde & eksempler*. REKON Press.

I. Andersen, A-L., Andersen, R., Napoleone, A., Brunø, T. D., Kjeldgaard, S., Nielsen, K., Sorensen, D. G. H., Raza, M., Bilberg, A., Rösiö, C., Boldt, S., & Skärin, F. (2023). *Paving the way for changeable and reconfigurable production: Fundamental principles, development method & examples.* REKON Press.

J. Andersen, A-L., Andersen, R., Brunoe, T. D., Larsen, M. S. S., Nielsen, K., Napoleone, A., & Kjeldgaard, S. (Eds.) (2022). *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems*. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-90700-6

K. Andersen, A-L., Brunoe, T. D., Larsen, M. S. S., Andersen, R., Nielsen, K., Napoleone, A., & Kjeldgaard, S. (2022). A Bibliometric and Sentiment Analysis of CARV and MCPC Conferences in the 21st Century: Towards Sustainable Customization. In *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems* (pp. 3-24). Springer, Cham. https://doi.org/10.1007/978-3-030-90700-6_1

L. Kjeldgaard, S. (2022). *Evaluating Reconfigurability in Production Systems*. https://www.youtube.com/watch?v=RfwrpN4OvQM&t=9s

M. Kjeldgaard, S. (2022). *Design and evaluation of reconfigurable production systems: enabling adaptability and resilience of a global production network*. https://www.youtube.com/watch?v=2U6levzgilk

CHAPTER 1. INTRODUCTION

This chapter introduces the PhD project by motivating the research effort. First, with a retrospective example from the automotive industry. Second, with an outline of the current industrial conditions and prospective paradigm shifts for environmental fit to mitigate challenges. Initially, from a broad scope, narrowing to the industrial partner.

In 1909, Henry Ford remarked, "*Any customer can have a car painted any color that he wants so long as it is black*" [1]. However, "*Ford maintained two production lines, one for the cars and one for the jokes*" [2]. Although apocryphal, they remain legion, as the famous remark was false at its inception [2]. Multiple colors were optional for Model Ts between 1908 and 1913 [2]. The decision to only make black cars was first made in 1914 due to production considerations [3]. The public quickly accepted the decision and forgot the colorful Fords as the price was cut in half [2]. The reduction was enabled by a paradigm shift towards *mass production* [4].

> "*When mass production started, individuality stopped. In order to reduce manufacturing costs and turn out automobiles in sufficient quantity to supply popular demand, producers had to evolve factory methods that permitted economical, high-speed operation. They had to concentrate the forces of men and machinery on the production of standard, stock-stamped motor cars. Instead of making different cars, each manufacturer simply made the same car over and over again. Automobiles that came from the same plant had less individuality among themselves than a nest full of eggs from the same hen*" [3,5].

Ford's production was not confined by the boundaries of one manufactory [3]. Some factories were responsible for producing parts, allowing no deviation even in color, as they utilized dedicated machinery and tooling to accommodate the volume and cost requirements and negate the risk of capital losses [4]. Others were responsible for the assembly of cars, using division of labor and moving transfer lines [3]. Moreover, the production boundaries were not even confined to the same continent [1]. Grey Model Ts were produced at the factory in Detroit, Michigan, United States of America, from 1908 [3]. Blue Model Ts were produced at the factory in Trafford Park, Manchester, United Kingdom, from 1911 [2]. The principles of mass production from back home were transferred offshore at an incremental, although fast, pace [1]. In retrospect, the distribution between continents to supply customers with different colored Model Ts was presumably sparse to nonexistent as the addition of transportation costs would be excessive. Nevertheless, different colored Model Ts were out-phased in the domestic markets because dedicated production for differentiated products rendered excessive costs, which customers were unwilling to pay for [3]. They wanted their first car at a cheap price and could not care less about its configuration [2].

The industrial conditions of the former century have evidently changed, prompting paradigm shifts for manufacturing firms to fit with their environment at equifinality to sustain competitiveness [6–12]. Globalization has led to fierce competition, market turbulence, fragmented demands, new product introductions, wide product ranges, and production decentralization [13–15]. The well-established, although antiquated, paradigms of mass production and dedicated manufacturing systems are unfit in light of these conditions, as they limit the responsiveness and utilization of capital-intensive assets [16–19]. In response, the paradigms of *mass customization* and *reconfigurable manufacturing systems* were proposed, which promote modular and platform-based products and manufacturing systems [20–22]. The systems' architectures comprise standardized platforms and interfaces with interchangeable customized modules for rapid and cost-efficient conversion of functionality within a product family [23–31]. In the automotive industry, *Volkswagen AB* applied the principles across the domains to create the *modulare querbaukasten* and *modulare produktionsbaukasten*, reducing asset investments by 30% and increasing productivity by 20% [32,33].

Despite the exemplary success, the principles are scarcely applied across industries, and manufacturers struggle as a consequence [34]. Especially the firms with a similar setup to Ford's, i.e., dedicated production systems in a global production network, are challenged [14]. They need to constantly change the production mix at their factories to chase an uncertain demand that fluctuates on variety, volume, timing, and location, and they struggle with the polylemma of production, transportation, inventory, and investment costs [13,14]. The challenge can be solved through adaptability, which can facilitate resilience to mitigate the impact of black-swan disruptions [14,15]. The paradigm of reconfigurable manufacturing systems has been proposed as an enabler of the decisive competitive capability, yet with a deficit of empirical evaluation [14].

This PhD project aims to bridge the deficit and support a specific industrial partner in their pursuit of environmental fit and competitive advantage through a paradigm shift.

The industrial partner competes in the wind energy industry with global demand and production. The range of products is vast and rapidly expanding with frequent new introductions. The size of products and components is immense, which scales to the systems used in production, storage, transportation, and installation. The customers specify localized production as an order qualifier, and the supply chain has recently been disrupted. In other words, the conditions mentioned earlier are especially present in the context of the industrial partner, but so are the monetary potentials of a sufficient paradigm shift. [35]

According to the current Chief Executive Officer at Vestas Wind Systems A/S:

> "*Modularization will enable us to optimize the entire value chain and lift industrialization to higher levels, which will ensure long-term competitive advantage for Vestas and accelerate the green transition.*"

CHAPTER 2. THEORETICAL BACKGROUND

This chapter presents the theoretical background of the PhD project. First, the three main manufacturing system paradigms are defined to provide a frame of reference for the paradigm shift of interest, i.e., from dedicated to reconfigurable manufacturing systems. After that, the enabling characteristics of reconfigurability and the levels of embodiment are defined to ground the context-specific design in scope. Then, the area of manufacturing system development and the challenge of financial evaluations are outlined to position the research effort and contributions. Finally, the level of global production networks is defined as it is essential to grasp the environment in scope.

2.1. MANUFACTURING PARADIGMS

Manufacturing is derived from *manu factum,* i.e., made by hand, and production is derived from *pro ducere*, i.e., lead forward [36]. Depending on regional contexts, one is defined as the subset of the other [3,37]. They are also used interchangeably [36] and will be throughout this dissertation and its appended papers. A system is the sum of interrelated parts with a purpose [38,39]. A production or manufacturing system is the collection of interlinked resources used to create outputs from inputs [36,37].

Manufacturing firms need to adapt to the conditions of their environment to sustain competitiveness and survive [38]. The conditions change over time and are triggered by internal or external drivers, prompting an extent of change to the manufacturing systems [17,18]. Like the firm, the systems must also fit with internal and external conditions to be efficient [6,7]. The systems are open as they interact with and adapt to their environment, although with resource boundaries that can be specified [40].

Throughout several industrial revolutions, multiple manufacturing system paradigms have been developed to fit with the change drivers of their age [15]. This has resulted in the Dedicated Manufacturing Systems (DMSs), Flexible Manufacturing Systems (FMSs), and Reconfigurable Manufacturing Systems (RMSs) [13,16]. In the current age of globalization, manufacturing firms need to adapt to a faster rate of new product introductions (NPIs), shorter product life cycles (PLCs), wider product variety, shorter delivery times, unstable demand, and various context-dependent drivers [13,17,18].

DMSs stem from the second industrial revolution of the 1900s, specifically the era of mass production [13,41]. DMSs have high capacity and low functionality, suitable for high volumes of low variety with stable demand [19,21]. DMSs have fixed, built-in, and pre-planned capabilities for immediate requirements [19,42]. DMSs are usually based on serial transfer lines with synchronized flow and automation [13,16]. DMSs are investment-intensive due to a long lifetime and a high throughput, resulting in low production costs if the capacity is utilized [19,43]. This necessitates a push tactic if the demand is unstable, increasing inventory costs [13]. If the demand changes, the tactic carries a risk of obsolete products and a reduction of lifetime utilization [17].

FMSs stem from the third industrial revolution of the 1970s [13]. FMSs have a low capacity and high functionality, suitable for low volumes of high variety [17]. FMSs have fixed, built-in, pre-planned, general-purpose, and apriori functionality [19,42]. FMSs are usually based on cells of computer numerical control machines [21,44]. FMSs are investment intensive with low throughput, resulting in high production costs and a revenue risk if demands exceed capacity [21]. FMSs have excess flexibility but are still at risk of low utilization if the functionality exceeds demand [13,19].

The archetypes of DMSs and FMSs carry an inherent dilemma of economies of scale or scope [21]. Mass Customization was introduced in the 1980s to mitigate the trade-off using modularity and postponement principles [20,45,46]. Within the paradigm, the archetypes are positioned on opposite sides of the differentiation point [13]. As an extension, RMSs were introduced in the late 1990s to solve the dilemma with rapid scalability and convertibility [21]. The rationale of RMSs is the capability to provide:

> "*Exactly the capacity and functionality needed, exactly when needed*" [13].

RMSs are suitable to accommodate unstable volume and variety demands, among other changes. Reconfigurability is, thereby, a dynamic capability that can facilitate a competitive advantage, especially in the current age of globalization [13,15,47]. The difference between the manufacturing system paradigms is illustrated in Figure 1. The position of RMS changes due to its dynamic capability to provide functionality and capacity on demand by conversion or scaling, resulting in new configurations.

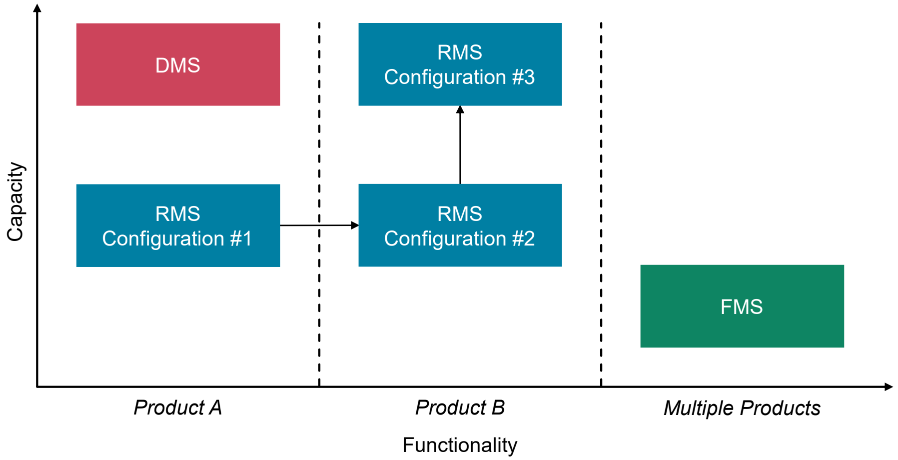

Figure 1: Manufacturing system paradigms. Adapted from [42].

2.2. RECONFIGURABILITY CHARACTERISTICS

The two primary characteristics of reconfigurability are convertibility and scalability [42]. Convertibility is the capability of the system to efficiently convert production functionality to new and existing parts within a family [19]. In contrast, scalability is the capability to efficiently scale production capacity [19]. These capabilities are supported by modularity, integrability, and customization [18]. Reconfigurability is enabled by the embodiment of the characteristics in the system's architecture [21].

Architecture is the structural composition of a system's functional and physical parts and interrelationships [38,48,49]. Modularity is the extent to which the architecture is composed of standardized discrete parts with independent functional bindings and standardized de-coupled interfaces to interchange modules across similar variants of systems [23–31]. Integrability is the interconnection of modules through interfaces [19,21]. Customization is the constraint on the system's functionality to a family with similar specifications, e.g., dimensions, geometries, and materials [19,21]. Standard parts and interfaces within a family denote the shared platform with commonality from which a set of variants can be derived [31]. These concepts are interrelated, stem from the product domain, and are relevant to manufacturing systems [21,50].

Within this dissertation and its appended papers, RMSs are defined as manufacturing systems with a modular and platform-based architecture of standardized platforms, standardized interfaces, and interchangeable customized modules for rapid and cost-efficient functionality conversion within a part family. An example of the conversion of an RMS architecture is illustrated in Figure 2. The diametric opposition is a system with an integral architecture composed of interdependent parts with coupled interfaces and interconnection [28,48]. The structural composition is usually more cost-efficient in the shorter term than the modular opposition [49]. Although only to the extent that requirements are stable, otherwise requiring a change of the complete system rather than a part of it, as in the case of DMSs [17,43,51,52].

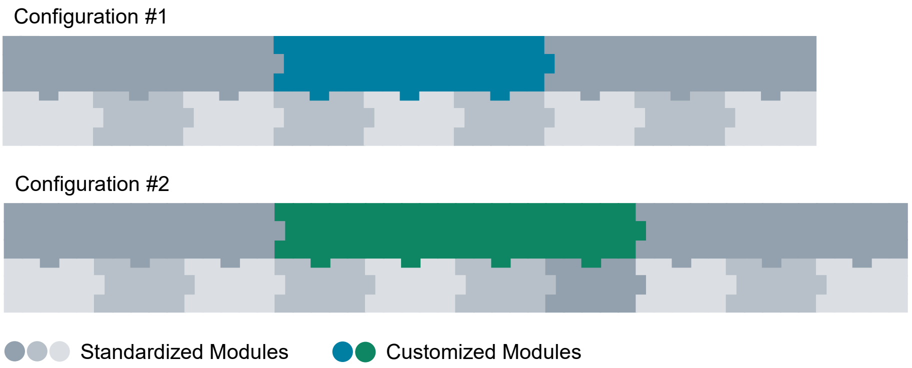

Figure 2: Modular architecture of reconfigurable manufacturing systems.

2.3. PRODUCTION LEVELS

Reconfigurability and flexibility are encompassed under the changeability umbrella. Changeability is the capability to make cost-efficient and timely changes on all levels of production [17,18]. Production can be structured in six hierarchical levels: network, factory, segment, system, cell, and station [17,53–57]. The levels are generic and may not be easy to distinguish or applicable in some cases, e.g., some firms do not operate with a network of factories, a factory of segments, or a system of cells [18,58,59].

Reconfigurability and flexibility are positioned on levels below the factory [17,18]. In contrast, transformability and agility are on the factory and network level, referring to the tactical change of the production mix of factories and the strategic response to changing market conditions [17,18]. It can be argued that reconfigurability on lower levels positively impacts the extent of changeability on higher levels [58,60]. The production levels and their related changeability classes are illustrated in Figure 3.

One level is explicitly labeled as the system, referring to the production lines [17,18]. However, a system can also be regarded as the constituents of the lines, down to the machines, equipment, and tooling [13,19,21,61]. Systems theory would argue that all levels are either a system or a system of systems [38,39]. The levels below the factory and their constituents will be referred to as systems throughout this dissertation and its appended papers to encompass the boundary of any kind of manufacturing system while maintaining a clear distinction of capabilities between higher and lower levels.

2.4. PRODUCTION DEVELOPMENT

In contrast to product development and Operations Management (OM), production development is a neglected and underreported area where research is scarce [62–65]. However, the research is necessary, as indicated in the following quote:

"*As industrial competition increases it becomes more apparent that improved levels of out-put, efficiency, and quality can only be achieved by designing better production systems rather than by merely exercising greater control over existing ones*" [36,66].

The aim of production development is either radical or incremental, i.e., develop new systems or improve already existing systems [36]. The radical is more suitable to comply with new requirements as it is not bound by the same constraints [36,66].

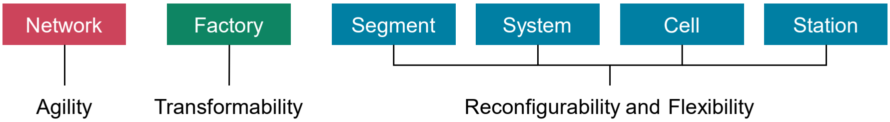

Figure 3: Production levels and changeability classes. Adapted from [17].

The development of RMSs can be characterized as radical as it deals with a paradigm shift. However, the realization of RMSs lacks support from the current research, which has primarily focused on discrete, narrow, and partial parts of the development, e.g., product family grouping, layout optimization, and configuration selection [67].

The development of RMSs takes outset in general production development, which is similar to product development, by means of stage-gate development, despite dealing with their own challenges [36,61,67–70]. These development methods differ slightly in scope, granularity, and overlap [67]. However, all propose the stages of requirement specification, conceptual design, detailed design, and implementation. The evaluation occurs within and between stages at the intermediate gates [71,72]. The stage-gate development is illustrated in Figure 4. In RMS development, emphasis is placed on the complexity of co-evolution and the criticality of financial evaluation [73–75].

RMSs are complex systems, and their development is a challenging task [58,76]. This is due to their capability to co-evolve with the product range and respond to demand uncertainty [73,77]. The complexity increases as reconfigurability can be embodied in several ways, to several extents [18,78,79]. Production development usually occurs at the tail end of product development, with less priority than products, imposing time and resource constraints on the development [36,80]. It usually leads to one-off DMSs that resolve the immediately present product and volume requirements that are subject to change over time, rather than RMSs with long-term properties for dynamic and changing requirements that must be embodied early in the design [36,81]. Platform-based co-development is proposed to solve the short-sighted dedicated development by the simultaneous development of both products and production systems [22,82]. This has at least been argued since 1995 related to integrated development, integrated, concurrent engineering, and design for manufacturing [50,83–88].

2.5. FINANCIAL EVALUATION

Evaluation is critical to justify the initial investment of RMSs, which exceeds DMSs due to their modular architecture with built-in convertibility [18,51,73,75]. The initial investment is a barrier to the industrial transition, although the long-term benefit of efficient response to uncertainty is recognized [34,89,90]. Evaluations are used to compare the feasibility and suitability of designs, and they are critical in development [36,73]. This is because 80% of the investment in systems is committed by decisions taken in the first 20% of the development [91,92]. Moreover, principal design flaws resulting from inferior early decisions are progressively complicated and expensive to correct in later stages, if even possible at all [70,84,93,94].

Figure 4: Stage-gate development. Adapted from [71].

Financial evaluations are periodically made between the stages to advance through the screening at intermediate gates [71,95]. The aim is to validate and substantiate the design alternatives' monetary benefits by comprehensive analysis [36,96–98]. The monetary quantification is the basis for decision-making with less bounded rationality and uncertainty [80,95]. In the industry, it manifests as business cases to justify the investment and persuade stakeholders [71,99,100]. In turn, to secure the managerial commitment and financial backing to advance the development [84,101–103]. It is especially critical, as resources are shared amongst development projects, creating scarcity due to competition from inverse interdependencies [104–106].

Engineers and managers alike prefer numbers over words [107,108]. However, they do not trust the numbers unquestioningly and are less likely to be persuaded [99]. It strengthens the filtration of inferior solutions by scrutiny, which raises the bar to pass. Accordingly, the financial evaluation should be grounded in comprehensive cost and performance analysis of the technical design and its intended operation according to the conditions of its environment where simulation or optimization models are favored in the field of operations and supply chain management [14,36,96,97,109].

However, qualitative, subjective estimates of upsides are also relevant because "*not everything that can be counted counts, and not everything that counts can be counted*" [110]. This is especially the case early in the development, where a comprehensive analysis takes time and effort [111,112]. This is unreasonable when concepts are not designed and infeasible due to resource scarcity. The financial evaluation is therefore suggested to occur in multiple stages [71,95]. Starting with quick-and-dirty analyses [111,112]. Ending with comprehensive quantitative modeling [14,96,97,109]. The lifetime costs of the manufacturing system paradigms are illustrated in Figure 5.

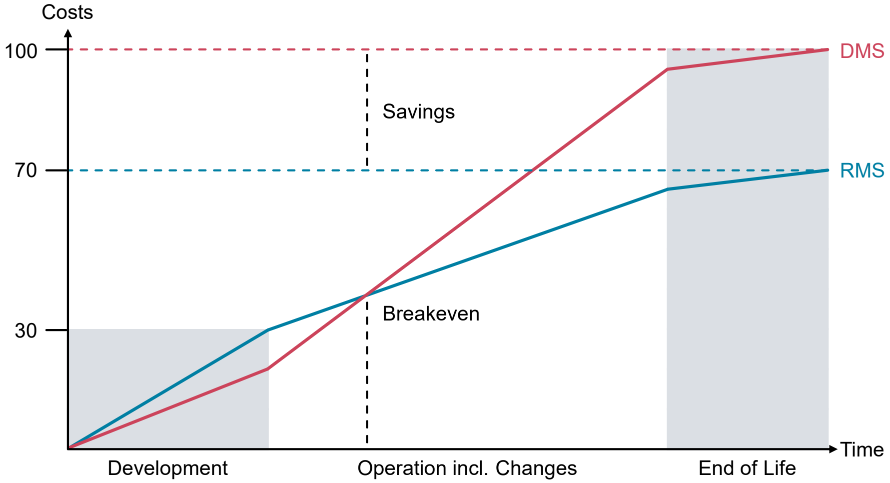

Figure 5: Lifetime costs of manufacturing systems. Adapted from [51].

2.6. PRODUCTION NETWORKS

From a resource perspective, Global Production Networks (GPNs) are geographically dispersed production entities interlinked by material, information, and financial flows [14,113]. In 1984, Miles and Snow [114] predicted that dynamic network organization of production would emerge in the new millennium to fit global changing markets. The prediction held [115]. Today, GPNs are the most critical form of organization and account for nearly 80% of global trade [14,116,117]. The management of GPNs has, therefore, progressively become a focus of attention in research [113,118–120].

The architecture of GPNs has vertical, horizontal, hierarchical, geographical, and proprietorial dimensions related to the tiers, entities, locations, and owners [113]. GPNs encompass supply chains of up- and downstream tiers, e.g., material suppliers, system vendors, component factories, pre-assembly sites, and installation sites [14]. GPNs encompass footprints of entities divided by geography due to, e.g., offshoring necessitating transport [114–118]. GPNs can be divided into segments according to the markets, i.e., regions or products [119]. GPNs can exceed a firm's boundary via outsourcing, joint ventures, partnerships, mergers, and acquisitions [120–122]. GPN architectures form incrementally in response to changing conditions [123–126]. GPNs are thus complex, dynamic, and open systems [113,127]. Their complexity and size constrain their ability to pivot towards changes, making them susceptible to a lag with a risk of failing to keep pace with the dynamic conditions of today [14,116,128,129]. Focal GPNs are defined by the boundaries drawn from the perspective of an OEM and their scope [113,130,131]. The construct of focal GPNs is applied throughout this dissertation and its appended papers. There is a trade-off between the roles for low-cost and close-to-market production, which is related to the GPN phenotype [118].

GPN phenotypes refer to the architecture of factories and interrelations [119]. Based on an industrial analysis [132], Meyer and Jacob [118,133,134] proposed five generic phenotypes, since acknowledged in research [14,114,135]. The phenotypes differ on economies of scale and scope versus local adaptation and transaction costs [118]. The fifth phenotype is of interest throughout this dissertation and its appended papers.

> "*The fifth phenotype, the Web Structure, is characterized by the fact that all production plants are able to manufacture all products being offered. Using this phenotype, local adaption as well as the utilization of economies of scale are low on one side. On the other side, due to excess resources and capacities, the production network can breathe in case of volatile demand, and capacity utilization can be smoothed. This is a unique feature which makes the Web Structure superior in terms of flexibility and agility. As it combines the benefits of centralization with benefits of high capacity utilization and close to-market production, the Web Structure is propagated as being the future phenotype for industry. Even today, it is the most common phenotype*" [14].

CHAPTER 3. INDUSTRIAL BACKGROUND

This chapter presents the industrial partner's context, motivation, and requirements, which have situated and driven the research effort throughout the PhD project.

The PhD project is part of the national research program Manufacturing Academy of Denmark (MADE). Specifically, the third research platform, MADE FAST (Flexible, Agile, and Sustainable production enabled by Talented employees), in the third work package on agile production systems. The industrial partner is Vestas Wind Systems A/S. Vestas provided the relevant problems and requirements to address by designing and validating rigorous contextual solutions. The PhD project is also affiliated with the national research project: development of Reconfigurable Production (REKON). It provided the opportunity for comparative studies at different case companies.

3.1. CONTEXT

An overview of the company, market, product, and production characteristics of the industrial partner is provided in Table 1 and is outlined in the following paragraphs.

Table 1: Overview of the industrial context.

Characteristic		Description
Company	Name	Vestas Wind Systems A/S (founded in 1945).
	Size	Global LME with 29,000 employees.
	Industry	Capital goods for the wind energy sector.
	Position	Largest OEM with 169 GW of 906 GW installed
Market	Segment	Onshore and offshore wind energy.
	Reach	Installed capacity in 88 countries and five regions.
	Share	13.3 GW of 77.6 GW installed capacity in 2022.
Product	Product	Onshore and offshore wind turbines.
	Variety	≥ 18 turbines across five platforms in the portfolio.
	Specification	Rotor diameter up to 236 m with 363 MWh in 24 hrs.
	Life-cycle	Ranges between two years and two decades.
	Introduction	More than one new turbine introduction per year.
Production	Context	Manufacturing of blades and assembly of nacelles.
	Volume	Approximately 3,500 turbines per year.
	Network	21 factories in 11 countries across five regions.
	Paradigm	A mix of dedicated and flexible production systems.

Vestas is a Large Manufacturing Enterprise (LME) with 29,000 employees [136]. Vestas operates in the capital goods industry for the energy sector. Vestas is the largest Original Equipment Manufacturer (OEM) benchmarked on installed wind turbines of 86,537 and installed wind capacity of 169 GW as of June 2023 [137,138]. Vestas is the global market leader in wind energy, with 13.3 GW of the 77.6 GW installed wind capacity in 2022 [35,136,138]. The market comprises the onshore and offshore wind energy segments for North and Central Europe, the Mediterranean, North America, Latin America, and the Asian Pacific [137]. Vestas has a Business-to-Business (B2B) and Business-to-Government (B2G) model and is engaged throughout the complete value chain, i.e., from development, manufacturing, and installation to service [136].

The energy sector competes on Levelized Cost of Energy (LCoE) as the order winner of projects in reverse auctions, i.e., tenders [139]. LCoE [€/MWh] can be improved by reducing costs or increasing performance, i.e., Annual Energy Production (AEP) [35]. AEP [MWh] can be improved by increasing the swept area by the rotor diameter by the blade length or by increasing the captured wind speed by the rotor height by the tower height [140–142]. These specifications constitute the primary technical enablers of competitive advantage and require the resolution of various constraints [141]. In layman's terms, the OEMs compete in a race for larger turbines suited to various site conditions, e.g., wind classes, etc. The derived effect is an increased rate of New Product Introductions (NPI) due to increased competition [143].

Vestas' NPI rate is more than one new turbine per year [137,144]. The Product Life Cycle (PLC) varies from the V90 with two decades to the V116 with two years [137]. The active product portfolio comprises 18 wind turbines with different rotor diameters across five platforms [137]. The rotor diameters vary from the V90 to the V236, and the latter set the world record in 2023 for most power output, i.e., 363 MWh in 24 hours [145]. The production volume is currently ~ 3,500 turbines per year [137,144]. The demand is expected to grow, as the installed wind energy capacity of 906 GW in 2022 must increase to meet the anticipated 2-3 TW demand in 2030 [35,136,146].

The critical components of wind turbines consist of the blades, nacelle, hub, tower, and powertrain. The blade geometries vary with a one-to-one relation to wind turbines due to the dependency between the blade lengths and rotor diameters. In contrast, the nacelle geometry is standard in each platform. The blade root diameters are standard in each platform due to the dependency between the blade and nacelle interfaces. The blade max chord is common in families due to family-based design. [147–149]

The PhD project was scoped with a primary focus on blades but was later expanded with a secondary focus on the nacelle. Blade production was deemed most relevant due to (i) a higher production volume and longer cycle times, which creates a need for more factories and systems to enable the required capacity, and (ii) larger dimensions and variety of products, which also scales to the geometry-dependent manufacturing systems [150].

The former increases the number of investments, and the latter the cost of tangible assets. Together, increasing the investment intensity and the improvement potential.

The derived impact of the wind turbines' scaling can be portrayed using the disclosed information of the V164 as an example. The nacelle has a length of 20 meters, height and width of eight meters, and weight of 390 tons [151]. The blades have a length of 80 meters, root diameter of 4.6 meters, and weight of 33-35 tons [150,151]. The blade shell mold has a length of 80 meters, width of 6.6 meters, height of 5.5 meters, and weight of 50-75 tons [152]. The scale sets requirements for factories' infrastructure, e.g., shop floors with a length of 220 meters and a width capable of handling upwards of six blade molds, partially due to the cycle time of, e.g.,.,, 24-38 hours [153–155]. Moreover, the scale also constraints transportation; e.g., a V236 blade shell mold was necessitated to be split into ten modules to make its transportation feasible [154].

The production context is manufacturing for blades and assembly for nacelles. The global production network comprises 15 blade factories and seven nacelle factories in 11 countries across five regions [136]. The former has gradually been outsourced to a near-equal division, and the latter is retained in-house. The production paradigm is a mix of dedicated and flexible systems. The production setup is primarily manual, with little automation. The planning policy is a mix of made-to-order and made-to-forecast.

3.2. MOTIVATION

The motivation for reconfigurability is rooted in the ability to accommodate changes. The drivers of changes comprise external and internal conditions in the case context. Selected drivers in the industrial case are illustrated in Figure 6. It presents ten drivers, their development patterns, and the percentual increase over time.

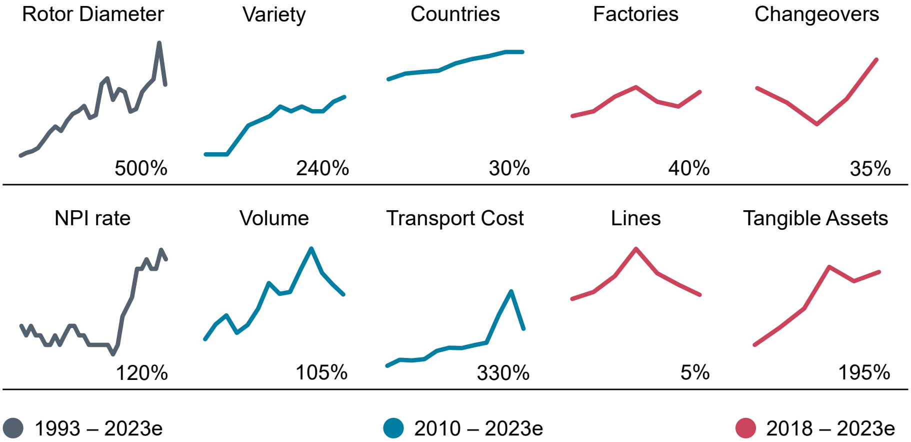

Figure 6: Change drivers in the industrial case. Based on [136,137,144].

To varying extents, the interrelated drivers necessitate changes. The NPI rate and PLC increase the variety. The demand impacts the production volume and the number of countries to supply. The volume, reach, and extent of local content requirements affect the number of factories to balance the regional production mixes. The variability in demand on volume, variety, and location impacts the number of reconfigurations and installations. The reconfigurations, installations, dimensions, and NPI rate affect the number of investments in tangible assets. The distance between factories and sites, product dimensions, and global disruptions impact transportation costs.

The majority of change drivers have increased somewhat steadily, some even by leaps and bounds, taking the differing horizons into account. Yet, the patterns also show a disruption of the pandemic in reduced production and increased transportation costs.

3.3. REQUIREMENTS

In 2012, Vestas designed its first modular product. In 2014, the initial success paved the way to embark on a committed journey. In 2020, modularization became one of the most critical strategic priorities, i.e., a must-win battle, to combat the increasing complexity of a diversified portfolio of larger products. From 2023, the next step was to implement the modularization principles throughout the value chain. In 2020, the development of RMSs was initiated to implement the principles of modularity in the production domain. It posed the PhD project with three questions:

I. What should be reconfigurable?
II. How do we enable reconfigurability?
III. What are the benefits of reconfigurability?

In addition, two main focus areas were to be considered by the research in the pursuit of answering the three questions. The first was multiple financial evaluations, as the firm operates with a policy of business case certainty and stage-gate development. The second was the scope of the global production network, as the firm operates with over twenty factories and hundreds of manufacturing systems. These focus areas were required to be present in the evaluations of suitable systems and potentials and the evaluations of conceptual and detailed designs. The firm also hypothesized that RMSs could enable adaptability and resilience of the global production network. However, the exact potentials proved challenging to quantify, which formed a sub-focus on the financial evaluation.

Based on the requirements from the industrial partner, the relevance and research topic of the PhD project lies in the intersection between three research areas:

I. Reconfigurable manufacturing systems.
II. Global production networks.
III. Financial evaluations.

CHAPTER 4. STATE OF THE ART

This chapter presents the state-of-the-art literature related to the research topic of the PhD project. First, the rationale of the RMS paradigm from its inception to the present is outlined. After that, the methods for identifying and evaluating RMS potentials are presented. Then, the quantitative models for the financial evaluation of RMS designs are presented. Hereafter, works on evaluation in the context of GPNs are outlined. Finally, the deficits and propositions related to the research topic are presented. The chapter summarizes and expands upon the reviews by Kjeldgaard et al. [156–162].

Throughout the 1990s, the RMS paradigm was developed with the rationale to rapidly and cost-efficiently cope with an increasing pace of unpredictable changes, e.g., NPI frequency and demand mix variability [163–169]. Throughout the 2000s, RMS was umbrellaed under CMS to accommodate the challenges of globalization, e.g., fierce competition, market turbulence, product heterogeneity, and demand fragmentation [13,17,18,114]. The challenges increased during the 2010s to the extent that dynamic capabilities are indispensable for global OEMs to sustain competitiveness in fierce global markets with uncertainty and volatility [16,43,131,170]. At the outset of the 2020s, the rationale for RMS has reached a detrimental breaking point due to the emergence of black swan events requiring OEMs and GPNs alike to be adaptable and resilient to changing and disruptive conditions [15,116,171–173].

4.1. EVALUATION OF RMS POTENTIALS

The identification and evaluation of RMS potentials are positioned within the stage of requirement specification towards the gate of conceptual design. The aim is to screen the suitability of manufacturing systems for reconfigurability embodiment based on technical, operational, or financial performance. In essence, to answer which should be reconfigurable and motivate their redesign based on the performance potentials.

Qualitative case studies were conducted by Heim et al. [174] in 2014 based on works from 2006-2012 [175–179] and by Boldt et al. [180] in 2021 based on a method from 2020 [181]. The studies evaluate the extent of reconfigurability enablers' embodiment in present manufacturing systems. Their approach can be applied to evaluate how reconfigurability is enabled in systems [67,182]. However, it cannot be applied to evaluate which systems are suitable to be reconfigurable, which is needed by industry as it can be advantageous in some and a wasted investment in others [43,58,76,183].

Andersen et al. [207] conducted a quantitative case study in 2015. The study evaluates the reconfigurability potential of improved production capacity in past manufacturing systems. The scenario and data-based approach towards a pragmatic quantification of what-if potentials can motivate industrial redesign. However, a prospective approach promotes a greater extent of urgency than a retrospective by linking the motivation to the burning platform of NPIs [34,82,183]. Moreover, the approach delimits the impact of reconfiguration time on production capacity, which is proposed for inclusion [184].

Bejlegaard et al. [185] conducted a quantitative case study in 2016. The study mainly evaluates the reconfigurability potential of reduced variety and reconfiguration time in future manufacturing systems. The measures are suitable for evaluation as they have been validated in industry [58,61,186]. However, the study is ambiguous on the calculation of the potentials, which constrains reproducibility in other cases [187,188].

Case-validated mixed methods were proposed by Coppini et al. [189] in 2017, by Fries et al. [190] in 2023, and by Boldt et al. [191] in 2023. The methods are used to evaluate the reconfigurability potential of reduced investment and operational costs of future manufacturing systems. The measures are suitable for evaluation as they have been validated in industry [43,52,192]. The methods require a pre-selection of systems to evaluate, which is less ideal in the context of a GPN due to a broader scope [193].

Andersen et al. [194] proposed a case-validated mixed-method in 2018. The method is used to evaluate the paradigm of changeability in present manufacturing systems. The method includes a fit-gap mapping between the current and suitable paradigms, which supports the identification of discrepancies and conformities [73,74,195].

Schou et al. [196] proposed a case-validated mixed-method in 2020 based on methods from 2018-2019 [193,197,198]. The method is used to evaluate the changes to present manufacturing processes. The method also includes a fit-gap mapping, similar to the method proposed by Andersen et al. [194], albeit on the specification level between new requirements and current capabilities. The method thereby supports identifying if requirements exceed or comply with capabilities, which processes can be reused for NPIs, and which specifications constrain reusability [34,183,199,200]. This means the method aids in evaluating whether, e.g., flexibility is suitable, but also how flexible it should be and on which specifications. However, as manufacturing processes are scoped, the method does not support identifying which systems enable and constrain the capabilities, necessitating further analysis to identify a suitable system for redesign [61]. Moreover, as both the method proposed by Andersen et al. [194] and Schou et al. [196] delimits the quantification of potentials, they are less suitable to motivate suitable manufacturing systems for redesign [34,82,183].

4.2. EVALUATION OF RMS DESIGNS

The financial evaluation of RMS designs is positioned across the stages and gates of conceptual and detailed design. The aim is to evaluate and compare alternative designs of manufacturing systems based on their financial performance grounded in their technical and operational performance. In essence, to determine which design is most suitable for detailed design or implementation based on their performance.

In 2004, Wiendahl and Heger [51] introduced a method for the financial evaluation of CMSs relative to DMSs. The method applies break-even analysis on the Life-Cycle Costs (LCCs) of Manufacturing System Alternatives (MSAs). The method contributes with an evaluation of the lifetime reconfiguration investments in addition to the initial investment, which the traditional approaches solely focus on [18,36]. The method also contributes with a scenario-based approach to incorporate uncertainty. The inclusion of LCCs and scenarios is critical to evaluate the long-term benefits of RMSs, which is needed to advance the industrial transition [73,74,89,90,201].

In 2008, Milberg and Möller [202] provided a framework for the financial evaluation of CMSs. The framework suggests a probabilistic analysis on the Net Present Values (NPVs) of MSAs. In 2008, Kuzgunkaya and ElMaraghy [203] provided a model for the financial evaluation of RMSs relative to FMSs. The model applies numerical analysis on the NPVs of MSAs, calculated by Linear Programming (LP). The model contributes with an optimization approach, which is suitable to capture the complexity of RMSs in terms of multi-dimensional capabilities and context-specific embodiments [34,43,76,204]. The model also contributes with a parameter of lifetime production capacity. The parameter is critical to capture the RMS potential of improved lifetime capacity utilization and the derived impact of reduced investments [34,205].

In 2014, Niroomand et al. [206] provided a model for the financial evaluation of RMSs relative to FMSs and DMSs, which expands upon earlier works from 2012 [205]. The model optimizes the allocations of production mix and resource investments among MSAs, calculated by Mixed Integer Programming (MIP) and validated by discrete event simulation. The model contributes with the scope of a factory with MSAs and variables for ramp-up and reconfiguration time. The scope and variables support to capture the RMS potential of improved responsiveness to changes in production mix along with improved production capacity utilization [69,207–209].

In 2017, Gyulai et al. [184] provided a model for the financial evaluation of RMSs relative to DMSs, which expands upon earlier works from 2014 [210,211]. The model applies numerical analysis on the LCCs of MSAs, calculated by hierarchical LP. The model contributes with variables to reconfigure MSAs by interchanging modules, which is critical to evaluate design architectures of RMSs rather than reconfigurability as a generic capability [76,89]. Moreover, the model contributes with a rolling horizon heuristic to incorporate demand uncertainty, which supports to evaluate the long-term benefits of RMSs [34,204]. The heuristic stems from seminal works in OM research [212,213]. The rationale is still relevant as the heuristic imposes bounded rationality where RMSs can mitigate the compounding impacts of sub-optimal decisions [214].

In 2018, Andersen et al. [192] provided a model for the financial evaluation of RMSs relative to FMSs and DMSs. The model uses probabilistic analysis on the discounted total costs of MSAs, calculated by Monte Carlo simulation. The model contributes with an empirical validation where an industrial design is evaluated in an industrial context, which is needed to advance the industrial transition [34,89,215]. Moreover, the model contributes with parameters of spatial capacity. The parameter supports to capture the RMS potential of improved spatial capacity utilization and the derived effect of increased functionality in the case of spatial constraints [58,60,183,205]. In 2021, Bortolini et al. [216] provided a model for the performance evaluation of RMSs, which expands upon an earlier work from 2019 [217]. The model applies Numerical Analysis on the reconfiguration time of MSAs, calculated by LP.

In 2018, Becker et al. [218] provided a model with utility for the financial evaluation of RMSs in GPNs, which expands upon earlier works in 2018 [219] and 2017 [220]. The model applies probabilistic analysis on Total Network Costs (TNCs), calculated by MIP. The model contributes with the scope of a Local for Local phenotype. Herein, the model contributes with variables for transporting manufacturing system modules between factories. However, the model assumes a fixed set of modules is available and delimits additional supply. The latter is critical to evaluate the impact of suppliers' capacity and lead-time constraints on factories' responsiveness [183,221].

In 2019, Tian et al. [222] provided a model with utility for the financial evaluation of RMSs in GPNs, which expands upon earlier works in 2018 [223]. The model uses numerical analysis on TNCs, calculated by MIP. The model contributes with the scope of a mixed chain and local for local phenotype and variables for transporting products from factories to sites. The variables support to capture the RMS potential of reduced transportation costs and investments in the case of local content constraints [58,60].

In 2021, Epureanu et al. [224] provided a model for the financial evaluation of RMSs in GPNs, which expands upon an earlier work from 2018 [225]. The model applies numerical analysis on TNCs, calculated by hierarchical LP. The model contributes with a scope of a reversed hub and spoke and variables for the inventory of products. The variables support to capture the RMS potential of improved inventory costs in case of mix variability and reduced investments to prepare for peak periods [58,60]. The model also contributes with a disruptive scenario, which supports to evaluate the RMS potential of increased adaptability and resilience of GPNs [173,186,207,226].

In 2023, Klenk et al. [127] provided a model with utility for the financial evaluation of RMSs in GPNs that expands upon earlier works from 2021 [227] and 2018 [228]. The model applies numerical analysis on TNCs, calculated by MIP. It contributes with a scope of a mixed chain and web structure. The latter is the prevailing phenotype in the industry and is projected as the suitable phenotype for the future [14,229].

4.3. EVALUATION IN GPN CONTEXTS

The area of GPNs has recently gained traction in research. Nevertheless, there is still a research deficit on the intersection of RMSs and GPNs. The novel research works on evaluation in the context of GPNs are outlined in this section, although they cannot *be positioned within any stage or gate of development. However, they are outlined as the works provide a novel scope and a set of considerations that can contribute as an additional facet or layer to the research area of evaluation within RMS development.*

Treber et al. [122] provide a method to evaluate the reallocation of resources between factories in GPNs. Aguila and ElMaraghy [230] provide a system dynamics model to evaluate the performance of GPNs against disruptions. Buergin et al. [231] provide a MIP model to evaluate the allocation of production mix among factories in GPNs. Biswas et al. [186] provide a framework to evaluate enablers of adaptability in GPNs. Liao et al. [232] provide a MIP model to evaluate designs of closed-loop GPNs. Shen et al. [233] provide a MIP model to evaluate the performance of GPNs. Verhaelen et al. [234] provide a method to evaluate new locations of factories in GPNs. Verhaelen et al. [235] provide a framework of measures to evaluate the performance of GPNs. Verhaelen et al. [208] provide a method to evaluate production ramp-up efficiency for SMEs in GPNs. Hamzaday et al. [236] provide a MIP model to evaluate designs of assembly systems in GPNs. Roudbari et al. [237] provide a MIP model to evaluate designs of reverse logistics in GPNs. Pourhejazy et al. [238] provide a MIP model to evaluate designs of assembly systems in GPNs. Rajesh [239] conducted a study on enablers of resilience in GPNs. Chen et al. [240] provide a MIP model to evaluate enablers of resilience in GPNs. Peukert et al. [116] provided a method to evaluate production and logistics-related contingencies against risks in GPNs.

4.4. DEFICITS AND PROPOSITIONS

This section summarizes the deficits and propositions within state-of-the-art literature related to the research topic of the PhD project. First, within the research area of RMS. Then, in the research area of GPN. Finally, in the intersecting research area.

OEMs in the automotive industry have pioneered the implementation of RMSs and capitalized on cost-efficient responsiveness [52,241–245]. A prominent example is the *Modulare Produktionsbaukasten* for the *Modulare Querbaukasten* by *Volkswagen AB*. It reduced asset investments by 30% and increased productivity by 20% [32,33]. However, the widespread implementation of RMSs is scarce, although practitioners acknowledge the potential [34,52,89,204,246]. The number of publications on RMS has increased by 185% throughout the 2010s, relative to the 2000s [215]. The research has mainly focused on the desk-based creation of theoretical methods and models for family formation, enabler assessment, configuration optimization, design automation, layout planning, and process scheduling [34,183,204,215,221]. However, the research provides limited support to the industrial transition as it does not aid in mitigating two primary barriers [34,204,215]. A barrier is a deficit of empirical research on the design, evaluation, and potential of RMSs [58,189,247]. In this regard, there is a need for case studies on relations between the multi-dimensional and context-dependent requirements, enablers, and potentials in different industrial contexts [34,43,58,76].

A second barrier is a deficit of methods and models as decision support to financial evaluation [67,68,73–75]. A deficit is a method to support the pre-design evaluation of manufacturing systems suitable for reconfigurability embodiment [34,76,183,204]. The method should include a prospective fit-gap mapping between the requirements of NPIs and the current capabilities of manufacturing systems on a specification level to create urgent motivation for redesign [73,82,195,199,200]. The method should also quantify the potential of improved investment costs, operational costs, reconfiguration time, and production capacity [43,52,58,61,184]. The method should have a mixed approach for time- and resource-efficient identification of an area for comprehensive evaluation [248–251]. The method should include systematic practical guidelines and industrial validation to support application [182,185,252]. A second deficit is methods to support the design of RMSs [61,67,74,204]. The method should include the value chain requirements and constraints of the GPN [43,253].

A third deficit is models to support the post-design evaluation of the impact of RMSs on financial performance [34,73,89,215,221]. The model should include rolling- and scenario-based quantification of LCCs to incorporate uncertainty and evaluate the long-term benefits of RMSs to advance the industrial transition [74,90,183,201,214]. The model should be based on optimization to accommodate the complexity of multi-dimensional capabilities and context-specific embodiments of RMSs [34,43,76,204]. The model should be monolithic rather than hierarchical, as the evaluation is recursive and not iterative, to integrate strategic, tactical, and operational decisions [254]. The model should reconfigure systems by interchanging modules to evaluate RMS design architectures rather than the generic capability [76,89]. The model should include the lifetime and ramp-up capacity of the manufacturing systems and the spatial capacity of the factories to evaluate the impact on lifetime-, production-, and spatial capacity utilization, which affects the responsiveness of factories to changes in production mix [69,185,207,208,253,255]. The model should include the production, inventory, and transportation of system modules from suppliers to factories to evaluate the impact of capacity- and lead time constraints on the responsiveness of factories and the potential of reduced investment costs and inventory costs [58,60,183,221]. The model should include the transportation of products from factories to sites to evaluate the potential of improved transportation costs [58,60]. The model should be scoped towards GPN contexts [15,34,43,224,226]. The web structure phenotype is especially of interest to both research and industry alike [14,229]. The model should be able to evaluate the adaptability and resilience of GPNs [172,173,186,207,226].

There is a deficit of decision support for the design and operation of GPNs [14]. Three separate, although interlinked, tasks of the core area have become a focus of attention in research because of an increasing industrial need for support to the complex tasks [14,227,235,256,257]. One critical task is the structural footprint design [258–260]. There is a deficit of enablers of adaptability and resilience to accommodate changes, uncertainty, and disruptions [15,121,240,261–264]. The deficit is related to a call for research on enablers of low-cost and close-to-market production to negate hysteresis

[14,208,265]. A second critical task is the allocation of production mix at factories, where the increased product variety and demand variability are critical challenges for OEMs in GPNs [122,266,267]. With globalization, Koren [13] emphasizes the need to "*deliver the desired product, in the correct quantity, at the correct time, at the right place*". A third critical task is the allocation of resources where there is a deficit of models to support the configuration of assets, functionalities, and capacities among factories [263,268–272]. The decisions are only reversible at a significant cost due to a high investment intensity, which impacts the long-term financial performance of the GPNs [127,133,227,234,273]. The impact of inferior decisions can be mitigated, and the cost and time efficiency of GPNs can be improved with a shift towards CMSs for a decisive competitive advantage [14,208,265]. The potential cost savings can be up to 45%, whereas most manufacturing firms only realize about 10% [122,133,235]. However, the evaluation of improvement potentials in GPNs is a challenge and lacks exploration in research [122,235,274–276]. All of the aforementioned is interlinked, where the lack of support for the financial evaluation of CMSs in GPN contexts leads to inferior decisions and untapped potential for adaptability and resilience. Therefore, research is proposed on methods to identify improvement potentials and optimization models to evaluate the extent of the potentials [121,123,258,264,269,277–279].

There is a deficit of research on RMSs in GPNs [15,204,226]. Veritably, less than 4% of RMS research covers GPNs [59]. The deficit limits manufacturing firms' shift to RMS and its benefits [204,253,280,281]. The benefits of RMSs in GPNs have recently gained traction in research [186,282–284]. Even to the extent that potentials have been identified in industrial cases [58,60]. However, the realization requires decision support throughout the development [34]. In light of recent black-swan disruptions, RMSs have been hypothesized as an enabler of the adaptability and resilience of GPNs [172,173,186,207,226,282]. However, there is a deficit of empirical validation of the hypothesis [14,224]. It relates to deficits on methods for the pre-design evaluation of RMS potentials in GPNs and models for the post-design evaluation of the financial performance impact of RMS in GPNs [15,34,204,224].

Based on the deficits and propositions mentioned earlier, the two main contributions needed in research to support global manufacturing firms can be summarized as:

> *A method to support pre-design evaluation of manufacturing systems suitable for the embodiment of reconfigurability to comply with NPIs in GPNs based on the potentials of investment costs, operational costs, reconfiguration time, and production capacity.*

> *A model to support post-design evaluation of the financial impact of RMSs in GPNs with a three-tiered web structure using rolling- and scenario-based optimization of the production, inventory, and transportation of units from vendors to factories to sites where the ramp-up, lifetime, and modular interchange of systems is considered.*

CHAPTER 5. RESEARCH OBJECTIVE

From the industrial background, there is a need to support the financial evaluation of reconfigurable manufacturing systems in the context of global production networks. From a review of state-of-the-art literature in the research area, it is evident that there is a deficit of sufficient decision support. To solve the industrial problem and bridge the research deficits requires the design of suitable methods and models.

The research objective is therefore:

> *To design and validate methods and models for the financial evaluation of reconfigurable manufacturing systems in the context of global production networks.*

Global production networks are characterized by geographically dispersed production entities from the perspective of an original equipment manufacturer. The PhD project aims to provide decision support to the structural design of an adaptable and resilient three-tiered web-structure production footprint with a mixed low-cost close-to-market strategy, facilitated by the dynamic allocation and configuration of production mix, resources, functionalities, and capacities in accordance with fluctuations in demands. Reconfigurable manufacturing systems are hypothesized as an enabler of the before mentioned, and they are characterized by modular and platform-based architectures of standardized platforms and interfaces with interchangeable customized modules for rapid and cost-efficient conversion of functionality within the range of a part family. The research aims to aid the industrial transition by providing decision support for the financial evaluation of potentials and designs throughout the development.

The associated research questions are, therefore:

RQ1. How can the potential of reconfigurable manufacturing systems be identified and evaluated in the context of global production networks?

RQ2. How can the financial impact of reconfigurable manufacturing system designs be evaluated in the context of global production networks?

CHAPTER 6. RESEARCH DESIGN

This chapter presents the research design of the PhD project. First, the rationale of the adopted research paradigm is argued. Then, the associated research framework is outlined. After that, the research methodology is presented. Finally, the research methods are presented. An account of how the framework, methodology, and methods have been operationalized in the research papers is outlined in the respective sections.

6.1. RESEARCH PARADIGM

The worldview adopted in the PhD project is pragmatism due to the aim of creating and applying solutions that work to solve practical problems in the real world using a plurality of means [285]. The research paradigm applied in the PhD project is Design Science Research (DSR). DSR is a problem-solving paradigm at its heart [286,287]. Design is derived from *désignáre*, i.e., to point the way, with purposeful advancement, value orientation, and a focus on making it work [288]. Design science is rooted in engineering and aims to systematically solve ill-structured problems by the process of exploration through design [38,287,289,290]. It is suitable for OM research as it seeks to design a means to an end to solve practical problems, usually related to an undesired gap in performance [287,291]. DSR is selected as the research paradigm of the PhD project as it is a suitable means to diagnose and solve the practical ill-structured problems experienced by the industrial partner in their real-world context.

6.2. RESEARCH FRAMEWORK

The PhD project applies the DSR framework proposed by Hevner et al. [286,292], illustrated in Figure 7. It consists of three iterative cycles between three domains. The industrial environment is rooted in the context of the industrial partner wherein the problem space of interest to improve resides [38]. The knowledge base is rooted in the literature related to the research area of the PhD project, wherein deficits of interest to bridge reside. The research takes outset in the relevance and rigor cycles [286,287].

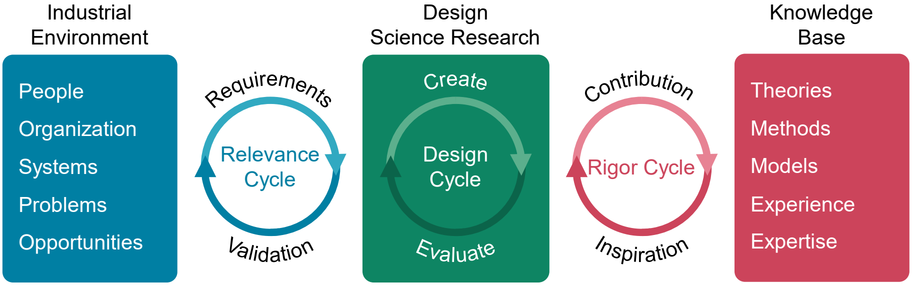

Figure 7: Design science research framework. Adapted from [286,292].

The relevance cycle is applied to define the practical problems and practical needs in the industrial environment by data collection and analysis, providing the requirements for creating and evaluating artifacts. The rigor cycle is applied to define the research deficits within the knowledge base and to draw inspiration for the research. The design cycle is applied to iteratively create and evaluate artifacts with functions that comply with the needs to solve the practical problems and bridge the research deficits using the drawn inspiration. The artifacts are validated in the industrial environment, and the generated knowledge is codified and contributed to the knowledge base. [292,293]

6.3. RESEARCH METHODOLOGY

The PhD project applies the DSR methodology illustrated in Figure 8, proposed by Johannesson and Perjons [294]. The methodology is used to concretize the interrelated activities of the iterative research effort and provide systematicity and transparency [287,294]. The methodology is representative of the two DSR cycles related to papers C and G. The research of papers C and G are the main contributions to the two research questions, supported by the anteceding and fragmented research efforts of papers A, B, D, E, and F. The cycles, activities, and relations of the papers are listed below.

A. Based on a relevance cycle and, to a lesser extent, a rigor and design cycle. Inspiration is drawn and instantiated to define problems and needs.
B. Based on a relevance cycle and, to a lesser extent, a design and rigor cycle. Needs are defined, and inspiration is drawn to create an artifact. The artifact is validated in two cases and is compared to the inspiration.
C. Based on a relevance, rigor, and design cycle. Needs, functions, and deficits are defined, and inspiration is drawn to create and evaluate an artifact. The artifact is validated in a case and is evaluated relative to the deficits.
D. Based on a relevance cycle and, to a lesser extent, a design and rigor cycle. Needs, functions, and deficits are defined, and inspiration is drawn to create an artifact. The artifact is validated in a case.
E. Based on a relevance cycle and design cycle, and to a lesser extent, a rigor cycle. Needs and functions are defined, and inspiration is drawn to create and evaluate an artifact by trial-and-error testing. The artifact is validated in a case study to define deficits and needs to be met in Paper G.
F. Based on a rigor cycle and, to a lesser extent, a design and relevance cycle. Deficits are defined, and inspiration is drawn as inputs to paper G.
G. Based on a relevance, rigor, and design cycle. Needs, functions, and deficits are defined, and inspiration is drawn to create and evaluate an artifact. The artifact is validated in a case and is evaluated relative to the deficits.

6.4. RESEARCH METHODS

The applied methods in the PhD project include literature review, case research, and quantitative modeling. The combination of methods strengthens the research [295].

6.4.1. LITERATURE REVIEW

The literature review is essential to research. It supports discovering a research field's contributions, deficits, and propositions [296]. In turn, to guide, scope, inform, inspire, authorize, ground, and legitimize a research effort [187]. It is essential to ensure and prove the novelty of a theoretical contribution and the research rigor [297]. However, rigorousness rests on the trustworthiness [287]. Thus, internal validity and credibility are needed to mitigate errors, biases, and misinterpretations [298,299]. Moreover, reliability and consistency are needed to ensure reproducibility of the review process [187,188]. In essence, trustworthiness requires systematicity and transparency [300]. "*A review article should not be projected as a "black box" that leads the reader to make assumptions about "what was done" and "how" it was realized*" [301].

There are several types of literature reviews, and they can be combined [300–303]. The narrative review outlines contributions within a topic [301]. The critical review identifies deficits and directions for improvement by evaluating the weaknesses, contradictions, controversies, inconsistencies, problems, or discrepancies according to selected criteria and comparative analysis [301,304]. Reviews are usually selective to apriori knowledge, so they rarely comprehend all literature within a topic and are therefore vulnerable to subjectivity [301]. The risk of subjectivity can be mitigated, and trustworthiness can be increased by using protocols and procedures for searching, selecting, and evaluating contributions through systematicity and transparency [296].

Narrative and critical review combinations are applied in papers C and G. In contrast, a narrative review is applied in paper F. Protocols with search string and exclusion criteria are applied in papers C and F. In contrast, a protocol is delimited in paper G as it expands upon the review of paper F. Comparative analyses with evaluation criteria are applied in papers C and G to define deficits and improvements.

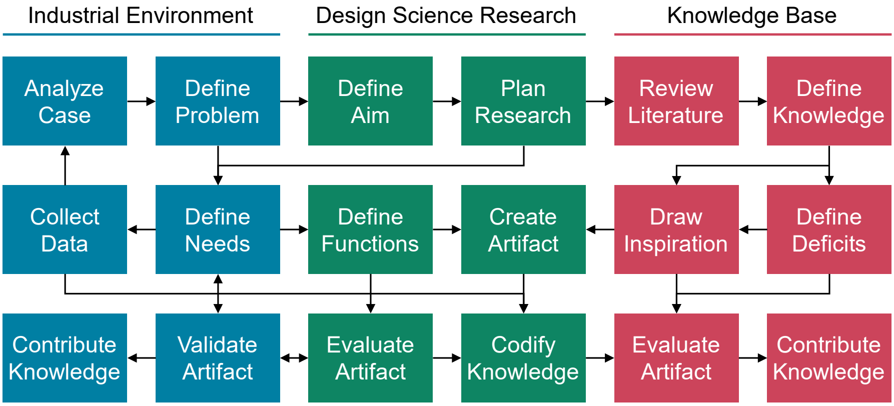

Figure 8: Design science research methodology. Adapted from [294].

6.4.2. CASE RESEARCH

During the Renaissance, scientists exclusively engaged in pragmatic research of the contemporary and specific contexts, with great rigor, due to apriori needs [305]. In contrast, the Scientific Revolution emphasized the formalization, generalization, and abstraction of knowledge to universal theory [306]. However, the OM field and the research area within have always been case-oriented to deal with practical problems as an engineering discipline [307]. Case research has mushroomed since the seminal article by Eisenhart [308]. Justifiably, the premises can be rejected for a renaissance of case research in the following direction [295].

> "*To the extent that contemporary and future scholars want to address contemporary organizational problems and establish credibility in the eyes of the managers of their times, focusing on the formal, the general, and the abstract can be antithetic… consequently potentially undermining situational groundedness*" [295].

As indicated above, case research has a duality, seeking situational grounding through empirical contextualization and generalizability by theoretical transcendence [295].

A critical aspect is case selection [248]. A statistician would argue for a size-sufficient and randomized sample for findings to be generalizable [308]. In contrast, there is a practical limit to the number of cases that can be studied without compromising depth, resources, and time [248]. Therefore, some scholars emphasize the selection of cases that "*possess specific traits that make them appropriate to address the research questions*" [248]. Other scholars argue for a few cases with polar characteristics [309].

Another aspect is approach selection [295]. Qualitative approaches focus on meaning and interpretation, whereas quantitative approaches focus on amount, intensity, and frequency [248,295]. It refers to the research's design, orientation, analysis, and data [250,295,310]. The approaches can be combined as a mixed method, which is suitable for addressing complex and multi-faceted questions as it allows fast exploration and delimitation to a relevant area for thorough analysis or validation [250,310].

A third aspect is mode selection [295]. The suitable selection depends on the research objective and the contemporary specific context [295]. One can distinguish between three modes: theory generation, theory testing, and theory elaboration [295]. These modes are idealistic and pure archetypes, which are not present in research, although an orientation towards one or another is usually found [295].

Theory generation aims to bridge gaps in theory. It is the most common in research [295]. It relies on the induction of emerging theory from analyzing situationally grounded data with less abstraction [311]. With a vantage point in established theory, situational grounding and generalization can be increased through comparison [312].

Theory testing aims at validating hypotheses. It is less common in OM research [313]. It relies on the deduction of hypotheses or propositions from contextualized theory and the induction or abduction from analyzing situationally grounded data to draw empirical conclusions [295]. Grounding and generalization can be strengthened by several analyses within a company and by invoking general mechanisms [295].

Theory elaboration aims at expanding theory. It relies on the simultaneous iterative abduction of general theory and empirical data in a balanced manner to reconcile the domains [295,314]. In contrast to theory testing, propositions are not made a priori of empirical findings [295]. Serendipity is stressed [315]. It requires the researcher to remain "*open to unanticipated findings and the possibility that the general theory requires considerable reformulation*" [295].

The PhD project has mainly focused on a single case company due to the requirement for funding, which necessitated collaboration with an industrial partner, where the scope required a lengthy and resource-intensive study in a somewhat unique context. With few exceptions, the case research of the PhD project's papers all apply traits of all three modes, with different combinations and main orientations. The research of paper A is oriented towards inductive theory generation in a cross-case study with a mixed approach. The research of paper B is oriented towards abductive theory elaboration in a multiple-case study with a qualitative approach. The research of paper C is oriented towards abductive theory elaboration by several instances of analysis in a case study with a mixed approach. The research of paper D is oriented towards abductive theory elaboration in a case study using a qualitative approach. The research of papers E and G is oriented towards abductive theory elaboration by several instances of analysis in a case study with a quantitative approach.

6.4.3. QUANTITATIVE MODELING

A common aphorism is that "*All models are wrong, but some are useful*" [316,317]. Models are imperfect representations as the absolute "*truth ... is much too complicated to allow anything but approximations*" [318]. It is necessary that "*When you construct a model you leave out all the details which you, with the knowledge at your disposal, consider inessential*" [319]. A "*scientist must be alert to what is importantly wrong. It is inappropriate to be concerned about mice when there are tigers abroad*" [316]. Yet, anything less than exhaustiveness will incur some uncertainty and, thus, bounded rationality upon decision-makers relying on the results [38,320]. However, pursuing perfection is tremendously resource-intensive and will, no matter what, accompany flaws detrimental to the utility [320]. Herein lies the trade-offs where the art of the discipline is to capture the proper extent of complexity within a sufficient boundary [321]. "*Models should not be true, but it is important that they are applicable*" [319].

> "*The question you need to ask is not is the model true? (it never is) but is the model good enough for this particular application?*" [322].

A quantitative model is an abstraction and approximation of a real problem situation to a set of variables and parameters with causal, quantitative interrelationships within a defined boundary [109]. Research in operations was initially based on quantitative modeling to solve real-life problems [109]. The discipline forked to generalized and context-specific models, aiming towards axiomatic or empirical models [109]. Since the 1960s, axiomatic models have been preferred, yet the tides turned at the dawn of the millennium [109]. The shift was due to a practical need for richer models that can be grabbed off the shelf with direct utility for specific problems in specific contexts [109]. A distinction is whether the model-based research is descriptive or prescriptive. The former can create an understanding of relationships [109]. The latter can predict the future state of a problem situation [109]. Nevertheless, model-based research can support decisions and actions to improve a situation [109].

Bertrand and Fransoo [109] state that empirical prescriptive quantitative modeling-based research relies on the execution of the phased cycle of the method for problem-solving from a systems view proposed by Mitroff et al. [320], illustrated in Figure 9. The first path, I-II, is to form a conceptual model of the problem situation, which defines the boundary of the variables in scope, the level at which they are treated, and their interrelationships by box-and-arrow representations [109,320]. The second path, II-III, is to form a scientific model in formal mathematical terms [320]. The third path, III-IV, is to derive one or multiple solution(s), if possible, using numerical, algebraic, optimization, or simulation techniques [109,320]. The fourth path, IV-I, is to feed the solution to the problem, and if decisions are made and corrective actions are taken, implementation has occurred [320]. The fourth path is rarely taken in research [109].

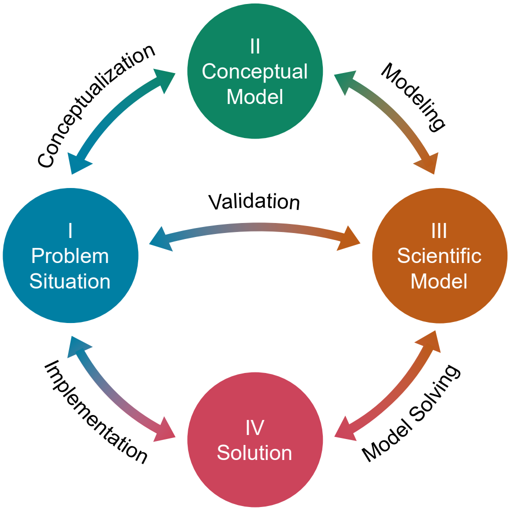

Figure 9: Quantitative modeling method. Adapted from [109,320].

Implementation is the challenging as preceding paths impose bounded rationality with risks on subsequent paths, and cooperation between actors with different skill sets is required [320]. The fifth path, I-III, is to validate the alignment, i.e., the extent of fit or gap, between the scientific model and the real problem situation [109].

Completing the pathed loop requires a broad range of skills. The conceptualization and implementation require holistic intuition and human relation skills. The modeling and model solving require formal analytic skills. The performance evaluation of the work is based on separate, distinct criteria. The conceptualization involves identifying relevant problems and is judged by the evaluands in their context. The modeling relies on mapping relevant variables and interrelations at suitable levels within a system. The model solving relies on deriving rigorous conclusions and is judged by scientific evaluators. The implementation relies on the impact within the context, judged by the evaluator responsible for managing the problem situation in the industrial context.

Validation relies on the continuous checking and perfection of the fit between the problem situation and the scientific model. Over-validation is a common research trap and a main risk, as indicated in the following quote. [320]

> "*This form of activity can readily degenerate into chronic insecurity, that of never being satisfied with any conceptualization or any model, and hence, of never getting around to the activities of Model Solving and Implementation. The search for the perfect conceptualization and perfect model can be classified as pathological forms of scientific activity*" [320].

Empirical prescriptive quantitative modeling-based research is executed in the PhD project, mainly in the research of paper G, based on the anteceding research of paper E, where a parity extent is present in-between, secondarily in the research of Paper C.

6.5. RESEARCH STRUCTURE

The structure of the PhD project is illustrated in Figure 10. The structure is composed of research questions answered by research papers using research methods. Papers are divided into two parts. The first part contains the publication outlet and an alphabetical enumeration representing the recommended reading sequence. The second part lists the applied methods, which indicates the relevance and rigor, along with the type of knowledge contribution. The arrows represent the logical interconnection of papers. The solid arrows represent artifact relationships, i.e., artifact design outputs are inputs to artifact design, e.g., the model of paper E provides inspiration to and is improved by the modeling in paper G. The dotted arrows represent case relationships, i.e., case research outputs are inputs to case research, e.g., the system with potential from paper C is the object to embody with a reconfigurable design in paper D.

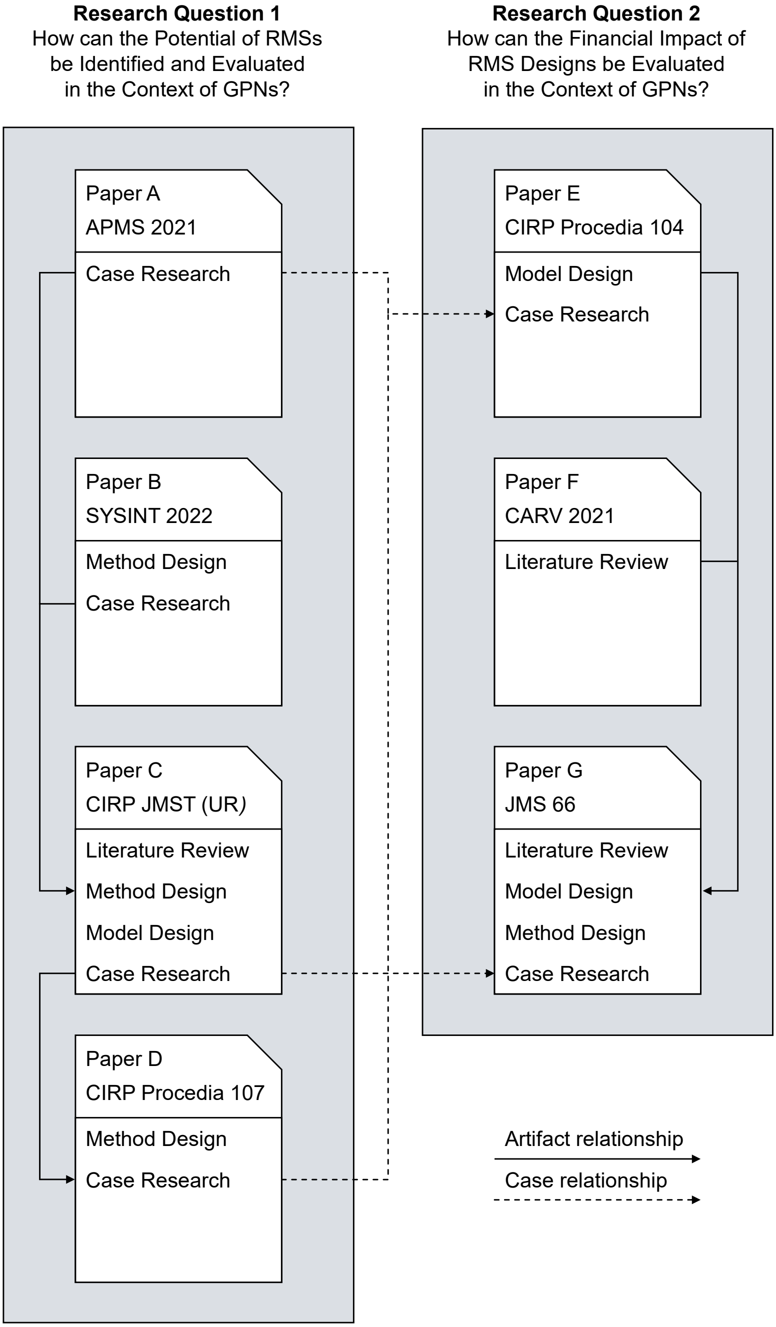

Figure 10: Structure of the PhD project.

CHAPTER 7. RESULTS

This chapter summarizes the PhD project's results, i.e., research papers. Each paper's title, aim, method, results, and implications are outlined in the following sections.

7.1. PAPER A

Title: Changeable Manufacturing: A Comparative Study of Requirements and Potentials in Two Industrial Cases

Aim

The research question is, "*What are differences in requirements and potentials of changeable manufacturing in different manufacturing settings?*" [156]. The aim is motivated by a lack of research on the relations between changeability requirements, enablers, and potentials in different real-life industrial contexts [34,43,58,76,194].

Method

The research is based on a case study inspired by the method provided by Eisenhart [308]. Two cases with distinct contexts are selected for the study. The case companies are an LME in the capital goods industry and an SME in the sporting goods industry. The case protocol is inspired by the questionnaire provided by Andersen et al. [194]. The data is collected using a mixed methods approach. The within-in-case analyses are inspired by the method provided by Andersen et al. [194]. The method is applied to map the requirements, paradigms, and characteristics to identify gaps between the current and suitable situation. After that, the potential of the suitable embodiment of paradigms and enablers is derived. The cross-case analysis compares the case contexts with the requirements and potentials.

Results

The research results in multiple potentials that are similar or different in the cases, depending on the requirements and context. The similar potentials comprise improved reconfiguration time, capacity utilization, lifetime utilization, and capital expenses. Although similar embodiments enable the potentials, the requirements differ, i.e., a high change rate of product dimensions versus a high change rate of product materials. The difference relates to the industry order winners, i.e., product performance versus personalization. A different potential is the reduction of transportation costs and an increase in sales revenue. It is present in contexts where fluctuating demands of global markets are supplied with a variety of large products through competitive tendering schemes with local content requirements from a footprint of multiple factories with frequent time- and capital-intensive changes to production functionality and capacity.

Implications

The research contributes to:

RQ1. Identify potentials of RMS in GPN contexts.
Inspire the design of the method in paper C.
Indicate the system to design by the study in paper D.
RQ2. Inspire the design of the model in paper E.
Indicate the system to be evaluated by the study in papers E and G.

The research contributes to theory with insights on similar and different requirements and potentials of changeability in two distinct industrial contexts, thereby bridging the stated research deficit [34,43,58,76,194]. Moreover, it supports to extend the seminal proposition of Koren [13] with the requirement to produce at the correct place and reconfigurability as an enabler to provide functionality where needed. The research contributes to practice with insights into suitable paradigms to accommodate context-specific changeability requirements and potentials.

7.2. PAPER B

Title: Facilitating Manufacturing System Development: Mapping Changeability Capabilities in Two Industrial Cases

Aim

The research question is, "*What are the industrial insights from applying an adapted and practitioner-oriented version of the method proposed by Schou et al.?*" [157]. The aim is motivated by a lack of research on a method to rapidly identify manufacturing processes' capabilities to accommodate product changes [34,183,204].

Method

The research is based on method design and case study. Inspiration is drawn from the method provided by Schou et al. [196] which supports to identify "*required changes in a manufacturing system, given a specific change within a product family/type*" [196]. However, it is resource-intensive for SMEs with budget and time constraints. Therefore, the method's scope is aimed towards the critical processes and products with changing characteristics for a manual ad-hoc impact evaluation using expert knowledge. The method is validated in multiple cases: an LME in the electronic goods industry and an SME in the sporting goods industry. In one case, the study is delimited to identify the current capabilities. In the other case, the study is expanded to evaluate the impact of product changes. Data is collected using a qualitative approach.

Results

The research results in an industry-applicable method to rapidly identify and evaluate manufacturing processes' changeability capabilities. It comprises five activities with a sequential and qualitative approach. It supports to identify new product requirements and current manufacturing capabilities to evaluate the impact of changes. It provides a process for the method's application, illustrations of matrices, and means of analysis. The descriptive study identifies the capabilities of twelve processes in one case. The prescriptive study evaluates the time to changeover and reconfigure the capabilities of seven processes to accommodate changing characteristics in the second case.

Implications

The research contributes to RQ1 by inspiring the design of the method in paper C. The research contributes to theory with an extension of the method provided by Schou et al. [196] to rapidly identify changeability capabilities, thereby bridging the stated research deficit [34,183,204]. The research contributes to practice with an industry-oriented, easy-to-use method that relies on expert knowledge to gain immediate, relevant insights with low effort.

7.3. PAPER C

Title: Evaluation of reconfigurability potentials in a global production network

Aim

The research objective is "*to create and apply a method to identify and evaluate the reconfigurability potentials of production systems in the context of a global production network*" [158]. The aim is motivated by a lack of research on a method to identify and evaluate RMS potentials in GPN contexts [34,43,58,73,76,183,204].

Method

The research is based on a systematic literature review, method design, and case study. The literature review is inspired by the methods provided by Pare et al. [300] and Hart [296]. Structured subject search and bi-directional snowballing are used to identify papers. Three exclusion phases are used to evaluate the papers' relevance. Methods are drawn from the relevant papers. Multiple criteria are used to classify and compare the methods according to their constituents. Research gaps are derived by evaluating the constituents according to extant literature. The method design draws inspiration from the review to bridge the identified research gaps. The method is validated in a case study. The case company is an LME in the capital goods industry. The study is initially delimited to the company's lead factories and then scaled to the GPN. Data is collected using the provided case protocol and a mixed methods approach.

Results

The research results in an industrial method to identify and evaluate manufacturing systems' changeability capabilities and reconfigurability potentials in GPN contexts. The method comprises four phases and ten activities with a sequential and mixed-method approach. It supports identifying new requirements and current capabilities to evaluate the reusability of systems and, hereafter, evaluate the potential improvement of reconfigurability embodiment in investment-intensive systems on four parameters. It provides a process for the method's application, a protocol for the data collection, an illustration of activities and matrices, formulations of calculations, and means of analysis. The case study results in fifty-five non-reusable systems for NPIs across four segments, of which nineteen systems are investment-intensive. The potential of one system was evaluated to improve the capital expenses by 42 M€, reconfiguration time by 58 weeks, operational expenses by 17 M€, and production capacity by 174 units.

Implications

The research is a primary contribution to RQ1 with a validated method to identify and evaluate RMS potentials in GPN contexts. Moreover, it also contributes to:

RQ1. Validate the potentials from the study in paper A.
Improve the design of the method in paper B.
Provide the system to design by the study in paper D.
RQ2. Indicate the system to be evaluated by the study in papers E and G.

The research contributes to theory with a method to identify and evaluate RMS potentials in GPN contexts, thereby bridging the before mentioned research deficit [34,43,58,73,76,183,204]. Moreover, the method bridges several sub-deficits. First, the method includes fit-gap mapping of new requirements and system capabilities on the specification level [73,82,195,199,200]. Second, the method includes measures to quantify the potential of improved investment costs, operational costs, reconfiguration time, and production capacity [43,52,58,61,184]. Third, the method supports time and resource-efficient identification of an area for comprehensive evaluation [248–251]. The research contributes to practice with support to identify suitable systems, evaluate potentials, create business cases, justify investments, motivate financial decisions, and convince stakeholders to initiate new development projects of RMSs in GPN contexts.

7.4. PAPER D

Title: Brownfield Design of Reconfigurable Manufacturing Architectures:
An Application of a Modified MFD to the Capital Goods Industry

Aim

The research question is, "*How can the modular function deployment be modified to support the design of reconfigurable architectures of brownfield manufacturing constituents with consideration of requirements and constraints throughout the value chain?*" [159]. The aim is motivated by a lack of research on a method to design RMS concepts according to value chain requirements and constraints [34,43,61,74,204].

Method

The research is based on a method design and case study. The method design modifies the Modular Function Deployment (MFD) proposed by Ericsson and Erixon [323]. The design (i) delimits requirement definition and functional definition, (ii) retains functional decomposition and means selection, and (iii) extends the driver definition, means evaluation, module evaluation, concept sketching, and concept evaluation. The extensions fall into two classes: inclusion from extant literature or addition inspired by the case company. The method is validated in a case study. The case company is an LME in the capital goods industry. Data is collected using a qualitative approach.

Results

The research results in extensions of the MFD. It is extended by the inclusion of eleven module drivers of the value chain to evaluate means, two design structure matrices to evaluate change and interface constraints of modules and a cladistics analysis to sketch the design. The method is also extended by the addition of a module indication matrix to evaluate splits and patterns of modules, and a mapping analysis to evaluate value chain constraints of the design. The case result is a modular and platform-based RMS design congruent with change, interface, and value chain constraints.

Implications

The research contributes to:

RQ1. Validate the potential from the study in papers A and C as a design.
RQ2. Provide the design to evaluate by the study in papers E and G.

The research contributes to theory with the design and validation of MFD extensions to design RMS concepts in value chain contexts, thereby bridging the stated research deficit [34,43,61,74,204]. The included extensions are the value chain drivers, design structure matrix, and cladistic analysis. The added extensions are a module indication matrix and a value chain analysis. The research contributes to practice by supporting the design of RMS concepts with value chain consideration.

7.5. PAPER E

Title: Towards a model for evaluating the investment of reconfigurable and platform-based manufacturing concepts considering footprint adaptability

Aim

The research question is, "*How can a supportive model be constructed, which can be applied in initial phases of manufacturing system development for evaluating the investment of reconfigurable and platform-based design concepts considering footprint adaptability?*" [160]. The aim is motivated by a lack of research on a model for the financial evaluation of RMS designs on the network level [60,192].

Method

The research is based on a model design and case study. The case company is an LME in the capital goods industry. The model design draws inspiration from the model provided by Asmussen et al. [254] to accommodate the requirements of the case. It is due to the utility of monolithic optimization models to handle the complex decisions and trade-offs across hierarchical levels present in actual cases. Data is collected using a mixed methods approach to validate the model.

Results

The research results in a quantitative model that uses optimization, specifically integer programming, to minimize the cost of a monolithic production plan. It comprises five indices, four decision variables, two calculated variables, three constraints, eight inputs, and five outputs for the objective function. It optimizes the investments, reconfigurations, production, inventory, and transportation across factories and sites of a production footprint. It supports the financial evaluation of RMS designs in the context of a production footprint. It provides tabularized descriptions of equations. The case input comprises context- and design-dependent data to evaluate multiple RMS designs relative to a baseline of a dedicated design across a horizon of fifty-two weeks. The case study results in average savings between 1-2%. The technical drivers of the improvement are indicated as reconfiguration time and module reusability. The operational drivers are indicated to be production capacity and transportation distance.

Implications

The research contributes to:

RQ1. Validate the financial potentials from the study in papers A and C.
RQ2. Evaluate the design of the system from the study in paper D.
Inspire the review of literature in paper F.
Inspire the design of the model in paper G.

The research contributes to theory with a model to evaluate the financial impact of real-life RMS designs in real-life contexts with a scope of manufacturing footprints, thereby bridging the stated research deficit [60,192]. Moreover, the model bridges several sub-deficits. First, the model includes variables for reconfiguration of systems by interchanging modules to evaluate RMS design architectures rather than a generic capability [76,89]. Second, the model includes the transportation of products from factories to sites to evaluate the potential of improved transportation costs [58,60]. The research contributes to practice with support to evaluate designs, create business cases, justify investments, motivate financial decisions, and convince stakeholders to advance ongoing development projects of RMSs in GPN contexts.

7.6. PAPER F

Title: Methods and Models to Evaluate the Investment of Reconfigurable Manufacturing Systems: Literature Review and Research Directions

Aim

The research question is, "w*hich methods and models are provided by state-of-the-art literature to evaluate the investment of reconfigurable manufacturing systems?*" [161]. The aim is motivated by a lack of research on the financial evaluation of RMS designs due to the practical criticality and complexity [36,73,90,243].

Method

The research is based on a literature review inspired by the method provided by Pare et al. [300] and Hart [296]. Structured subject search and bi-directional snowballing are used to identify papers. Three exclusion phases are used to evaluate the papers' relevance. Methods and models are drawn from the relevant papers. Multiple criteria are used to classify and compare the methods and models based on their constituents. Research deficits are derived by evaluation according to extant literature.

Results

The research results in a tabularized illustrated overview of three evaluation classes: qualitative methods, quantitative methods, and quantitative models. Four qualitative methods use an analytic hierarchy process on operational performance measures of RMSs with limited case validation and limited support for covering uncertainty. Four quantitative methods use index parameters on operational performance measures of several changeability classes of multiple objects, e.g., manufacturing systems, with case validation and minor support for covering uncertainty. Five quantitative models use optimization models on economic performance measures of several changeability classes of multiple objects with case validation and support for covering uncertainty by the application of scenarios.

Implications

The research contributes to:

RQ1. Ground the design of the model in paper E.
RQ2. Inspire the design of the model in paper G.

The research contributes to theory with a review of state-of-the-art literature on RMS evaluation, thereby bridging the stated research deficit [36,73,90,243]. Moreover, the review supports to derive a research deficit of quantitative models for comparative financial evaluation of RMS designs in production networks with uncertain lifetime requirements. The research contributes to practice with a decision tree to support the suitable selection of methods and models for the financial evaluation of RMSs.

7.7. PAPER G

Title: Enabling adaptability and resilience of a global production network: A model to evaluate capital and operational expenses of reconfigurable production systems

Aim

The research objective is "*to construct and apply a model to evaluate the expected performance impact, with respect to capital and operational expenses of reconfigurable designs of production systems within a global production network*" [162]. The aim is motivated by a lack of research on a model to evaluate the financial impact of RMS designs in GPN contexts [14,15,34,74,183,204,226].

Method

The research is based on a literature review, model design, method design, and case study. The literature review builds and expands upon the research presented in Section 7.6. Models are drawn from the identified papers. Multiple criteria are used to classify and compare the models according to their constituents. Research gaps are derived by evaluating the constituents according to extant literature. The model and method design draws inspiration from the review to bridge the identified research gaps. The model and method are validated in a case study. The case company is an LME in the capital goods industry. Data is collected using the provided case protocol and a mixed methods approach. A complete cycle of quantitative empirical modeling is executed, i.e., from reality to conceptual and scientific modeling to validation.

Results

The research results in a quantitative model that uses optimization, specifically integer programming, to minimize the costs of a monolithic production plan. It comprises six indices, six decision variables, thirteen calculated variables, thirteen constraints, twenty-one inputs, twenty-seven outputs where ten are part of the objective function, and two run parameters, resulting in eighty-eight constituents and fifty-five equations. It optimizes investments, reconfigurations, production, inventory, and transportation of systems, modules, and components across suppliers, factories, and sites of a GPN. It supports to evaluate the financial impact of RMS designs in the context of GPNs. It is supported by a method for collecting, analyzing, and applying data with heuristics, i.e., rolling horizon and scenarios to account for uncertainty. The research provides a conceptual model, a scientific model, matrices, a data protocol, and analysis means.

The case study results in average yearly savings of an RMS design, relative to a DMS design, by 5.4 m€ on operational expenses and 4.8 m€ on capital expenses through adaptability and resilience of the GPN. The technical and operational drivers of the financial improvement are discussed, along with the trade-offs in performance within and across scenarios. A polylemma of production, inventory, transportation, and investment costs was identified. The increased resilience of the GPN is demonstrated by the relative monetary savings in the pre-and post-pandemic scenarios, illustrated in Figure 11.

Implications

The research is a primary contribution to RQ2 with a validated method for financial evaluation of RMS designs' impact in GPN contexts. Moreover, it also contributes to:

RQ1. Validate the financial potentials from the study in papers A and C.
RQ2. Improve the design of the model in paper E.
Evaluate the design of the system from the study in paper D.
Bridge the research deficits from the review of literature in paper F.

The research contributes to theory with a model to evaluate the financial impact of RMS designs in GPN contexts, thereby bridging the before mentioned research deficit [14,15,34,204,226]. Moreover, the model bridges several sub-deficits. First, the model includes the scope of web-structures [14,229]. Second, the model includes variables for the production, inventory, and transportation of system modules [58,60,183,221]. Third, the model includes the systems' ramp-up and lifetime capacity and factories' spatial capacity [69,185,207,208,253,255].

The secondary theoretical contribution is the quantitative empirical case results, which address multiple research propositions. First, investigate the adaptability of GPNs as proposed by Lanza et al. [14]. Second, validate that RMSs can enable the adaptability of GPNs as proposed by Epureanu et al. [224]. Third, expand the theory of dyadic production strategies in GPNs as proposed by Lanza et al. [14]. Fourth, validate the top three tangible benefits of GPNs as proposed by Ferdows [324]. Fifth, validate that RMS can provide the capacity and functionality where needed, which elaborates on the proposition of Koren [13]. Sixth, validate that RMSs can enable the resilience of GPNs as proposed by Naimi et al. [226]. Seventh, validate enablers of resilience towards black swan disruptions as proposed by ElMaraghy et al. [15].

The research contributes to practice with support to evaluate designs, create business cases, justify investments, motivate financial decisions, and convince stakeholders to advance ongoing development projects of RMSs in GPNs. Moreover, it supports to evaluate hypotheses, assumptions, and scenarios. Finally, it supports the creation and optimization of production plans for strategic and tactical decision-making.

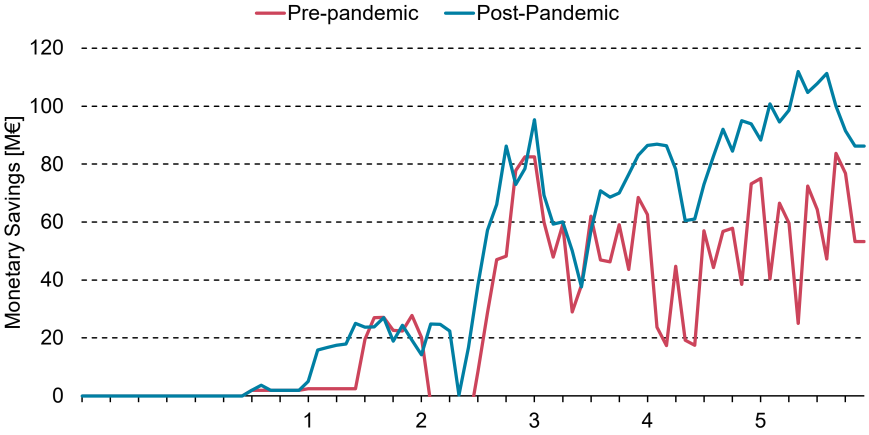

Figure 11: Savings of RMS relative to DMS design. Based on [162].

CHAPTER 8. DISCUSSION

This chapter presents a discussion of the theoretical contributions and the industrial implications of the PhD project. First, the theoretical contributions are evaluated by applying design science research frameworks. Then, the industrial implications are evaluated regarding the impact within the development at the industrial partner. Finally, the internal and external validity of the research is discussed.

8.1. THEORETICAL CONTRIBUTIONS

Design Science Research is applied in the PhD project to develop a means to an end, i.e., artifacts to solve problems [287]. A sufficient theoretical contribution necessitates that the means or the end must be novel [287]. Thus, the critical and central activity of evaluation, using suitable frameworks, is needed to ensure the rigor of the research and the novelty of the contributions [286,325]. Therefore, this section presents an evaluation of the contributions of the PhD project using multiple DSR frameworks.

Artifacts, i.e., design science products, are prescriptive knowledge [326]. They can be classified into four types: constructs, methods, models, and instantiations [326,327]. In brief, constructs are concepts, models are representations, methods are instructions, and instantiations are realizations [329]. Details are provided in the following quotes:

> "***Constructs** or concepts form the vocabulary of a domain. They constitute a conceptualization used to describe problems within the domain and to specify their solutions*" [326].
>
> "***A model** is a set of propositions or statements expressing relationships among constructs. In design activities, models represent situations as problem and solution statements*" [326].
>
> "***A method** is a set of steps (an algorithm or guideline) used to perform a task. Methods are based on a set of underlying constructs (language) and a representation (model) of the solution space*" [326].
>
> "***An instantiation** is the realization of an artifact in its environment... Instantiations demonstrate the feasibility and effectiveness of the models and methods they contain*" [326].

To varying extents, each type can contribute to research, depending on their novelty [327]. Methods correspond to the principles of function and models correspond to the principles of form. Models are usually conceptual or mathematical representations of a system of constructs and interrelationship [328]. The artifact can be instantiated by operationalization in their intended environment, e.g., by case research [286,327]. The prescriptive knowledge contributions of the papers are outlined in the following list.

A. Identification of changeability requirements, enablers, and potentials.
    - Instantiation of a pre-existing method in two industrial cases.

B. Identification of changeability requirements and capabilities.
    - Method with five activities and three analysis techniques.
    - Instantiation of the method in two industrial cases.

C. Identification and evaluation of RMS potentials in GPN contexts.
    - Method with four phases, ten activities, and twenty questions.
    - Diagrammatical model with four entities to represent the problem.
    - Mathematical model with 23 notations and 7 equations to calculate quantities, investments, and potentials of manufacturing systems.
    - Tabularized model with seven notations to specify requirements.
    - Tabularized model with ten notations to specify capabilities.
    - Diagrammatical models with two axes to analyze investments.
    - Constructs of bound flexibility and retrofit reconfigurability.
    - Instantiation of the above-mentioned artifacts in an industrial case.

D. Conceptual design of RMS concepts in GPN contexts.
    - A method with eleven activities and seven(teen) supportive means.
    - Three diagrammatical models for function-means mapping, system architecture mapping, and commonality-variety mapping.
    - Three tabularized models to evaluate potential system modules.
    - Constructs, i.e., module split drivers, module value chain coupling points, and extension modules.
    - Instantiation in an industrial case.
    - Instantiation of the above-mentioned artifacts in an industrial case.

E. Financial evaluation of RMS concepts in GPN contexts.
    - A descriptive model with twenty notations and four equations.
    - Constructs of functionality bottlenecks and footprint adaptability.
    - Instantiation of the above-mentioned artifacts in an industrial case.

F. Review of methods and models for evaluation of RMS.
    - A diagrammatical model for the selection of a suitable approach.

G. Financial evaluation of RMS designs in GPN contexts.
    - Diagrammatical model with six entities to represent the context.
    - Diagrammatical model with 14 entities to represent the problem.
    - Diagrammatical model with 43 notations and 45 interrelations to represent the architecture of parameters, variables, and objectives.
    - Mathematical model with 88 notations and 55 equations, to create and solve an optimization model of the problem.
    - Method with six activities to collect and analyze data.
    - Diagrammatical to create bounded-rationality in the evaluation.
    - Constructs, i.e., triadic cross-domain GPN web structures, low-cost close-to-market production strategy, and polylemma of investment, production, inventory, and transportation costs.
    - Instantiation of the above-mentioned artifacts in an industrial case.

Gregor and Hevner [327] provide a framework to evaluate knowledge contributions in DSR. The framework consists of two dimensions: solution maturity and problem maturity, from high to low, resulting in a two-by-two matrix with four quadrants:

I. Routine design, i.e., known solutions for known problems.
II. Exaptation design, i.e., known solutions for new problems.
III. Improvement design, i.e., new solutions for known problems.
IV. Invention design, i.e., new solutions for new problems.

The framework can be applied to evaluate the four types of prescriptive knowledge contributions: discretely or collectively as a coherent body. The body can be expanded with the descriptive knowledge gained by applying the artifacts in real-world contexts. A greater extent of knowledge can be contributed by the body and the expansion [327]. However, the evaluation can be tricky, as indicated in the following quote.

> "*A fundamental issue is that nothing is really "new." Everything is made out of something else or builds on some previous idea. When is something really novel or a significant advance on prior work?*" [327].

The coherent body of prescriptive and descriptive knowledge contributions of papers are evaluated qualitatively according to the dimensions and quadrants as proposed by Gregor and Hevner [327]. It is based on a comparison of the contributions to those in state-of-the-art which is presented in the papers. The position of the contributions and the extent of their novelty can be argued and an emphasis was placed on their relative position. The evaluation is illustrated in Figure 12 and is argued in the following list.

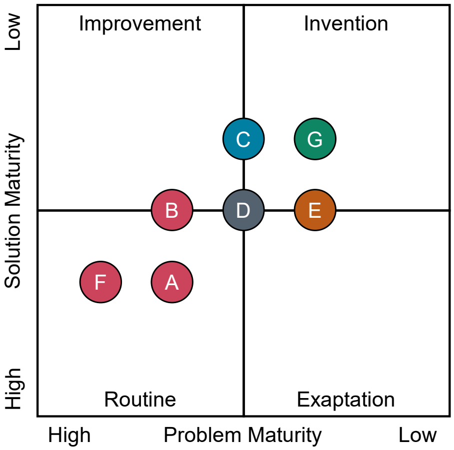

Figure 12: Evaluation of the knowledge contributions. Adapted from [327].

A. The position as routine moving towards exaptation design is reasoned as a known method is applied for a known problem in an under-explored domain where the descriptive knowledge contribution bridges the research deficits stated by Bortolini et al. [34] and Andersen et al. [58,194].
B. The position as routine moving towards improvement design is reasoned as a known method is modified and applied, with known constructs, for a known problem in an under-explored domain where the prescriptive and descriptive knowledge contribution bridges the research deficits stated by Singh Et al. [183] and Khanna et al. [204].
C. The position as an intermediate between improvement and invention design is reasoned as a new method is created and applied, with new and known constructs, for an under-explored problem in an under-explored domain where the prescriptive and descriptive knowledge contribution bridges the research deficits stated by Bortolini Et al. [34], Koren et al. [43,52], Francalanza et al. [73], and Russo et al. [76].
D. The position as an intermediate between the design quadrants is reasoned as a known method is modified and applied, with new and known constructs, for a known problem in an under-explored domain where the prescriptive and descriptive knowledge contribution bridges the research deficits stated by Koren et al. [43] and Najid et al. [74].
E. The position as an intermediate between exaptation and innovation design is reasoned as a new model is created and applied, with new and known constructs, for an under-explored problem in an under-explored domain where the prescriptive and descriptive knowledge contribution bridges the research deficits stated by Andersen et al. [192] and Christensen et al. [60].
F. The position as routine design is reasoned as a known method for a known problem is modified for an under-explored domain where the prescriptive contribution bridges the research deficit stated by Benkamoun [243].
G. The position as slight invention design is reasoned as a new model is created and applied, with new and known constructs, for an under-explored problem in an unexplored domain where the prescriptive and descriptive knowledge contribution bridges the research deficits stated by Lanza et al. [14,275], ElMaraghy et al. [15], Epureanu et al. [224], and Naimi et al. [226].

One can distinguish between several maturity and abstraction levels of contributions, ranging from the well-developed grand and mid-range theories to the nascent theories of situated artifacts [288,327]. The PhD project's contributions are bound to be nascent theories as "*empirical examination of solution designs in multiple contexts turns the solution design into mid-range theory of practice*" [287]. The counterargument of a slight advancement through the boundary is that "*the aim of mid-range theories is to develop a deeper understanding of a theory in a specific context of application*" [287].

Venable et al. [325] provide a framework to evaluate artifacts in DSR. It consists of four criteria: evaluand, timing, purpose, and paradigm which consider what, when, why, and how to evaluate [325]. The evaluand is the artifact to evaluate [329]. The timing can be ex-ante, intermediate, or ex-post the design [330]. The purpose can be formative to improve an evaluand or summative to select an evaluand for application [331]. The paradigm can be artificial within controlled abstractions or naturalistic in complex realities [332]. The criteria determine the evaluation strategy which can be quick and simple, human effectiveness, technical efficacy, or purely technical [325].

The artifacts of the PhD project are evaluated in Table 2 according to the framework proposed by Venable et al. [325]. The evaluands can be regarded as the designed evaluation artifacts or the evaluands the evaluation artifacts evaluate. The evaluation of both classes is labeled as class I or II and is outlined in the following paragraphs. The artifacts are evaluated in groups, determined by distinctiveness and precedence.

The artifact of paper A → C has the aim to evaluate potentials in the real environment by field studies and identify manufacturing systems suitable for reconfigurable design. The artifact of paper D has the aim to design and evaluate a technical reconfigurable concept in an abstract environment by criteria-based analysis. The artifact of paper E → G has the aim to test and prove if and which designs provide hypothesized benefits and the highest extent, in a controlled environment to decide on the implementation. The artifact of paper D was subject for summative ex-post evaluation by industrial stakeholders. The artifacts of papers A → C and E → G were subject for formative intermediate ex-post naturalistic evaluation in iterative succession in collaboration with the stakeholders. The artifacts were evaluated qualitatively by the subjective opinions of relevant stakeholders on measures of functionality, reliability, usability, and efficiency. Details on the industrial evaluation are provided in Section 8.2.

Table 2: Evaluation of prescriptive knowledge contributions.

Contributions		A → C	D	E → G
Class II	Evaluand	Potentials	Concept	Designs
	Timing	Ex-ante	Intermediate	Ex-post
	Purpose	Summative	Formative	Summative
	Paradigm	Naturalistic	Artificial	Artificial
	Strategy	Quick and simple	Technical	Technical efficacy
Class I	Evaluand	Method	Method	Model
	Timing	Intermediate	Ex-post	Intermediate
	Purpose	Formative	Summative	Formative
	Paradigm	Naturalistic	Naturalistic	Naturalistic
	Strategy	Effectiveness	Effectiveness	Effectiveness

8.2. INDUSTRIAL IMPLICATIONS

The prescriptive knowledge contributions of the research were applied throughout the industrial partner's internal development project that ran parallel to the PhD project. The position of the contributions within stage-gate development is illustrated in Figure 13, and the impact is outlined in the following list.

A. The contribution related to paper A made a direct impact by supporting the requirement specification in the first stage and the evaluation of the suitable manufacturing system paradigm for conceptual design at the first gate.
B. The contributions related to paper B made an indirect impact by inspiring the design of the contribution related to paper C.
C. The contribution related to paper C made a direct impact by supporting the identification and evaluation of manufacturing systems for reconfigurability embodiment during conceptual design in the first stage and at the first gate.
D. The contribution related to paper D made a direct impact by supporting the concept design of a reconfigurable manufacturing system in the second stage.
E. The contribution related to paper E made a direct impact by supporting the evaluation of a conceptual design for detailed design at the second gate.
F. The contribution related to paper F made an indirect impact by inspiring the design of the contribution related to paper G.
G. The contribution related to Paper G made a direct impact by supporting the evaluation of a detailed design for implementation at the third gate.

The quantitative model and results related to paper G, was presented to, and discussed with the stakeholders of the steering committee in the development project at Vestas. Together with the chief specialist within blade manufacturing concepts, it was decided to execute one last cycle of quantitative modeling. The model was redesigned with functionality to new requirements, populated with data from various domain experts, and instantiated to evaluate a complete relative to a partial design of reconfigurable blade molds. The results, i.e., relative monetary savings, are illustrated in Figure 14**.**

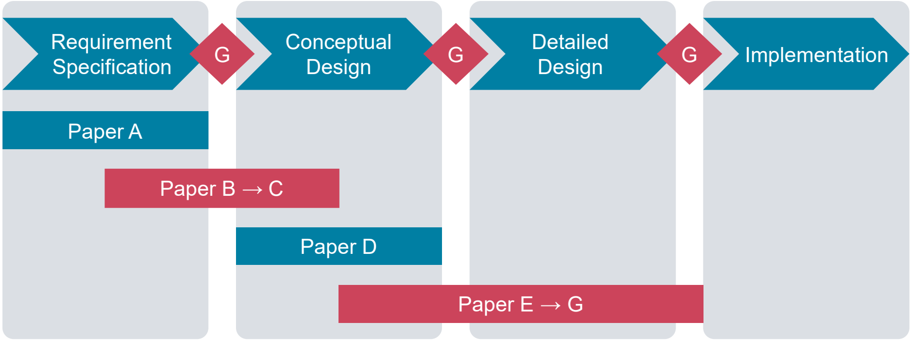

Figure 13: Contributions in stage-gate development. Adapted from [71].

The industrial evaluation, of the quantitative model and the results, is reflected by the final judgment of the problem situation manager, as outlined in the following quote.

> "*Det er en af de mest gennemarbejdede business cases jeg har set i mine femogtyve år hos Vestas… modelberegningerne passer sådan nogenlunde overens med den virkelighed jeg ser ind i. I hvert fald til et niveau der er godt nok… Vigtige beslutninger bliver taget på baggrund af dit arbejde*". [It is one of the most thorough business cases I have seen in my twenty-five years at Vestas… The model calculations fit somewhat with the reality I see. At least to a level that is good enough. Important decisions are being made on the basis of your work]. – Chief Specialist, November 2022.

The quoted important decisions that were made resulted in the following actions:

I. An action to seek patent protection for aspects of the *reconfigurable wind turbine blade moulds* [333,334]. An extract of a figure included in the cited patent applications is illustrated in Figure 15. The figure illustrates a design aspect of a modularized architecture of blade shell moulds.

II. An action to decommission V163 blade shell moulds with the partial design, i.e., standardized root and tip sections and customized mid-sections in 2023. It enables 75% reusability of the geometry-dependent structure of the mother shell moulds for configurations to new introductions within the same family.

III. An action to embody a blade mould with the complete design in collaboration with a strategic vendor in 2023 with the aim of technical validation.

IV. An action to allocate resources to a scoping project to identify and evaluate additional manufacturing systems suitable for reconfigurability embodiment across all component segments throughout the value chain.

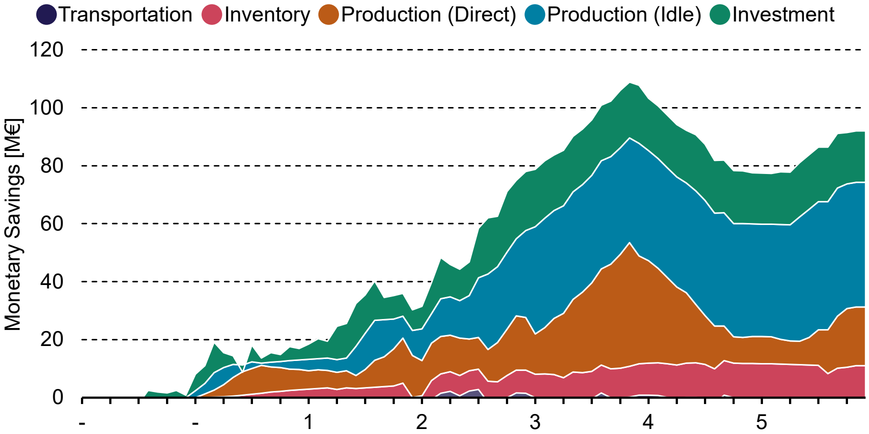

Figure 14: Savings of complete relative to partial RMS design.

Action IV prompted the design of the method and the case results related to paper C. A hundred system were screened across the factories in Lem, Ringkøbing, Nakskov, Lindø, and Hammel. The blade web moulds and jigs were evaluated as the systems with the highest potential as their geometry-dependency renders reusability for NPIs infeasible and as their cost and quantity renders high investment intensity. Recently, a scope of the value chain was proposed with the aim to screen for suitable systems used in storage, transportation, and installation. A prospect could be the blade fixtures that are used in the transportation which have historically been utilized less than two times and costs a couple of hundred thousand euros for the V236. The impact is thus, a set of systems for future development projects and a method for further screening.

During the development of the reconfigurable blade mold, a need to demonstrate the design and support the implementation emerged. To accommodate the need, a virtual factory simulation was designed and validated. A workshop was held with 23 experts. They were inquired through a questionnaire on the utility of the demonstrator on seven parameters using a five-point Likert scale. The parameters and their average score are: demonstrate the design to internal or external stakeholders (4.9), identify and mitigate collision risks between resources (4.6), train employees in reconfiguration tasks (4.6), specify and schedule reconfiguration tasks (4.2), allocate and balance resources to reconfiguration tasks (4.2), measure and optimize operational performance indicators (4.2); and measure and validate technical performance indicators (4.2).

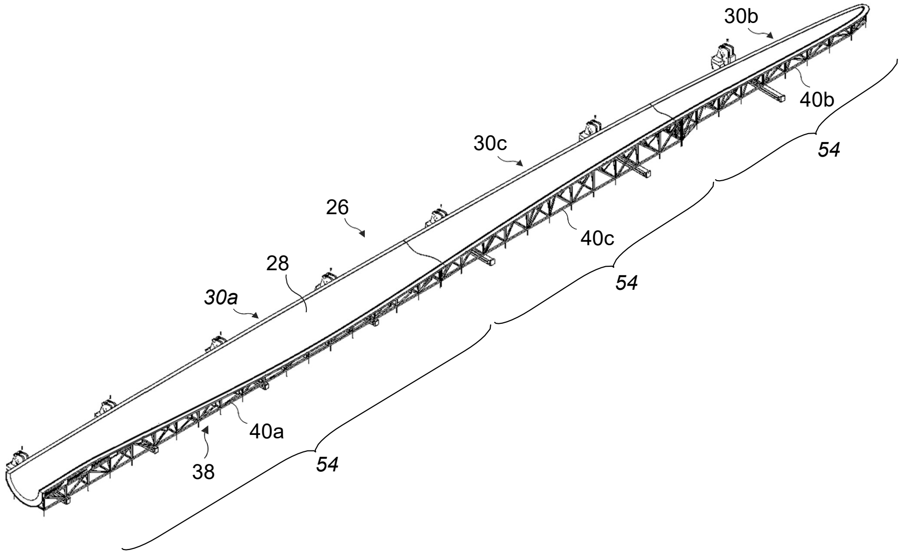

Figure 15: Reconfigurable blade shell molds. Retrieved from [333,334].

8.3. RESEARCH VALIDITY

This section discusses the internal and external validity of the research.

The empirical prescriptive quantitative modeling-based research related to the artifact produced throughout papers E → G went through the complete loop. However, the process was far from linear and highly iterative. The actual process through the paths can be represented as I→II→IV→I→II→IV→I→II→III→IV→I→II→III→IV→I. The conceptualization I→II, modeling II→III, and implementation IV→I were judged sufficient by the problem situation manager in the industrial environment as outlined in Section 8.2. The path of model-solving III→IV is arguably judged to be sufficient by the scientific community as indicated by the publication of paper G in a high-ranking journal, ranked eight (Q1) within Industrial and Manufacturing Engineering, with a SCImago Journal Rank Indicator of 2.7 (75% relative to the first) in 2022 [335].

Scholars within the research area of axiomatic modeling may judge a deficit of proper validation I-III. Although quantification of the fit between the model and the reality should have been more transparent, the pragmatic approach is deemed sufficient, as the implementation would otherwise be infeasible. Nevertheless, internal quantitative testing and comparison of the model results and the real problem situation data were executed. The quantitative parity validation was only possible for the DMS design by comparing with the historical demand and performance. Parity validation of the RMS design with forecast scenarios relied on internal and industrial qualitative evaluation. Only time will tell if the RMS design performs as expected, requiring a longitudinal study after its operationalization. However, when the experts already trust the results to fit somewhat with reality, to the extent that they will confidently base decisions and actions upon it, the model must be a good enough representation of reality.

The PhD project focused on situational groundedness by empirical contextualization to a greater extent than formalized generalizability by theoretical transcendence. Despite an inverse relationship, efforts have been made to strengthen generalizability. Descriptive and prescriptive knowledge contributions were produced using multiple instances of analysis in one or two case companies using general or context-specific mechanisms, and the results were compared to vantage points in established theory.

The contributions' position along the continuum is illustrated in Figure 16. Overall, the contributions or parts hereof have potential for generalized application in the wind turbine, maritime, aeronautic, and automotive industries. Primarily suitable in GPN contexts with a wide variety of sizeable and cost-intensive manufacturing systems.

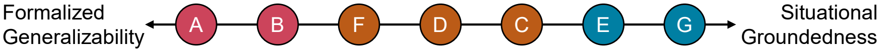

Figure 16: Generalizability and groundedness of the research contributions.

CHAPTER 9. CONCLUSION

The PhD project's research objective was *to design and validate methods and models for the financial evaluation of reconfigurable manufacturing systems in the context of global production networks* to solve industrial problems and bridge research deficits. Design science research, literature reviews, case research, and quantitative modeling were applied to create and validate novel artifacts as the prescriptive and descriptive knowledge contributions to achieve the research objective. The relevance is ensured by artifact validation at Vestas. The rigor is ensured by artifact grounding within state-of-the-art literature to bridge the research deficits. The following sections summarize the contributions and implications of the project related to the two research questions and propose directions for future research.

9.1. RESEARCH CONTRIBUTIONS

The first research question was *how can the potential of reconfigurable manufacturing systems be identified and evaluated in the context of global production networks?* The contributions of paper A are general RMS potentials of improved investment costs, lifetime utilization, reconfiguration time, capacity utilization, and context-specific RMS potentials of adaptability for a competitive advantage. The contribution of Paper B is a method to identify and evaluate changeability capabilities. The contribution of paper C is a method to identify and evaluate manufacturing systems suitable for the embodiment of reconfigurability to comply with NPIs in GPNs based on the potential to improve investment costs, operational costs, reconfiguration time, and production capacity. The contribution of paper D is a method to design RMS concepts in GPNs according to the requirements and constraints of the value chain.

The second research question was *how can the financial impact of reconfigurable manufacturing system designs be evaluated in the context of global production networks?* The contribution of paper E is a model to evaluate the financial impact of RMS designs in GPNs. The contribution of paper F is a classification of methods and models for financial RMS evaluation. The main contribution of paper G is a model to evaluate the financial impact of RMS designs in GPN contexts with a three-tiered web structure using rolling- and scenario-based optimization of the production, inventory, and transportation of units where the ramp-up, lifetime, and modular interchange of systems is considered. The second contribution of paper G is an industrial validation of RMSs as an enabler of adaptability and resilience of GPNs to demand fluctuations and black-swan disruptions.

9.2. INDUSTRIAL IMPLICATIONS

The methods and models supported the development of reconfigurable wind turbine blade molds at Vestas. Methods A and C supported the identification and evaluation of a suitable paradigm and system for concept design. Method D supported the design of concepts. Models E and G supported the evaluation of concepts for detailed design and the evaluation of designs for implementation. The design has a modular- and platform-based architecture with convertibility across different blade geometries and dimensions within families. Model G supported the decisions and actions to patent the design, commission the partial design in the current operations, and commission the complete design in the future operations. Method C supported the identification and evaluation of suitable systems for new development projects, e.g., blade web molds and jigs, and the decision to expand the scope to the value chain, e.g., blade fixtures.

The PhD project focused on situational groundedness by empirical contextualization to a greater extent than formalized generalizability by theoretical transcendence. Despite an inverse relationship, efforts have been made to strengthen generalizability. Descriptive and prescriptive knowledge contributions were produced using multiple instances of analysis in one or two case companies using general or context-specific mechanisms, and the results were compared to vantage points in established theory. The contributions or parts hereof have the potential for generalized application in the wind turbine, maritime, aeronautic, and automotive industries. The contributions are primarily suitable to be applicable in contexts with a global production network and a wide variety of sizeable and cost-intensive manufacturing systems.

9.3. FUTURE RESEARCH

A proposition for future research is to expand the evaluation model of paper G with parameters of transport emissions, material use, delivery lateness, and penalty costs.

Sustainability in manufacturing is relevant as it accounts for about a fifth of the global emissions [183,336]. The results indicate that RMSs can facilitate production near the demand and reduce transportation costs [162]. Arguably, transportation distance and emissions can also be reduced [172]. Moreover, the results indicate that RMSs can facilitate increased reusability and lifetime utilization [162]. Arguably, the material use can also be reduced [337]. However, there is a research deficit in sustainability evaluation using quantitative empirical modeling [34,338].

During field research in December 2022 at the pre-assembly site on Rønne harbor, there was a challenge with blade supply for installing 27 V174 at Arcadis Ost 1 in the Baltic Sea northeast of Rügen. The supply was designated from the Isle of Wright, which had recently installed a V174 mold for blades with a cycle time of about a week. Productivity issues resulted in delivery lateness, which resulted in heavy penalty costs. A retrospective analysis revealed that if the reconfigurable design had been applied for the offshore family, the production capacity could have been pooled from a V164 blade mold to increase productivity and mitigate delivery lateness and penalty costs.

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APPENDED PAPERS

A. Kjeldgaard, S., Napoleone, A., Andersen, A-L., Brunoe, T. D., & Nielsen, K. (2021). Changeable Manufacturing: A Comparative Study of Requirements and Potentials in Two Industrial Cases. In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems* (pp. 452-461). IFIP Advances in Information and Communication Technology, 631. Springer, Cham. https://doi.org/10.1007/978-3-030-85902-2_48

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F. Kjeldgaard, S., Andersen, A-L., Brunoe, T. D., & Nielsen, K. (2022). Methods and Models to Evaluate the Investment of Reconfigurable Manufacturing Systems: Literature Review and Research Directions. In *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems* (138-146). Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-90700-6_15

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