(Re)design of Complex Manufacturing Supply Chains

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INSIGHTS FROM AN INDUSTRIAL CASE

BY
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AALBORG UNIVERSITY
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ENGLISH SUMMARY

Firms continuously adapt the design of their supply chain to improve competitiveness and adapt to new market opportunities or downturns. It is therefore not unusual for daily media to report on firms undertaking significant structural changes in their supply chain. Often reported with a positive or negative angle, dependent on the changes' impact on local job creation and investment levels. Researchers have been similarly concerned with investigating a variety of aspects of the design of global supply chains. This includes mathematical models for optimal supply chain design, models for matching process capabilities and product requirements with the design of the supply chain, and governance models for the interaction between actors in global supply chains, among others. Despite the importance for the individual firm, the impact on the surrounding society, and extensive research, changes to supply chain design often result in unexpected problems and unrealised potential, challenging the initial rationale behind the implemented changes. This is observed in the form of unrealised cost reductions, increasing coordination cost, quality issues or missing flexibility. However, existing research has only to a limited extent focused on how the individual decisions, which form the supply chain design, are made, and what determines the effectiveness of such decision-making processes. Thus, there is a poor starting point for improving practice and working to reduce the negative consequences of erroneous supply chain design decision-making. This thesis seeks to address this challenge by investigating (1) how supply chain design decisions unfold and the impact of the decision-making process on realised changes in the supply chain design, (2) how the analytical foundation for such complex decisions can be improved, and (3) how organisational design influences the ability to decide on and implement supply chain design changes. These questions will be addressed in close interaction with a world-leading manufacturer of complex and capital-intensive products. In addition to the creation of new knowledge, the thesis thus also seeks to contribute to the development of the manufacturer's supply chain design capability.

The thesis consists of three parts, representing each research question. Initially, it is established how the complexity of the supply chain, and the complexity of the change to the supply chain, influence the decision-making process and the realised changes. The results reveal how a strong dependence on a financial assessment of the individual supply chain design change, combined with low transparency on the marginal impact of complexity, contributes to increasing complexity in the supply chain and acts as a barrier for realised strategic supply chain design changes. Furthermore, it is shown how the gap between the expected and realised outcomes of supply chain changes are influenced by the characteristics of the supply chain, as well as the amount and type of management attention during decision-making. This demonstrates the behavioural consequences of supply chain complexity and management attention, which should be considered when making supply chain design decisions. The results further point to ineffective decision-making due to limited comprehensiveness when assessing

supply chain design changes, a lack of consideration of supply chain system dynamics, and limited focus on vulnerability embedded in the supply chain designs being evaluated.

This insight creates the foundation for the second part of the thesis, addressing improvements in the analytical foundation for supply chain design decisions through several interventions conducted with the purpose of improving decision-making at the case company. This was done through the development, testing and analysis of several models and methods for decision support. This includes a conceptual model and process for a systematic evaluation of alternative supply chain designs. To support the decomposition and delimitation of the supply chain design decisions, a ratio reflecting the importance of the two asset types in the supply chain: production equipment and inventory is prposed. Through a mathematical planning model spanning strategic and tactical planning levels, it is shown how the A/I ratio is indicative of significant interactions between inventory development, workforce planning and capital assets should be considered in the design of the supply chain. Decisions that both, in practice and the existing literature, is usually treated separately. The model is further extended to quantify the value of volume flexibility when making supply chain design changes, to reduce the dependency of intrinsic managerial valuation. This work therefore also reflects that a significant challenge related to the design of the supply chain is the ability to predict the future system behaviour, e.g., inventory levels, and compare this system behaviour with other direct costs, such as the purchase price or labour cost. To support such evaluations, it is shown how the analysis of large quantities of operational data can support decentralised decision-makers in evaluating the impact of supply chain design changes on system behaviour. Finally, a model for analysing and comparing the vulnerability of the supply chain with the cost performance through a Pareto frontier is introduced.

In the third part of the thesis, the interaction between the organisational complexity and the task of supply chain design is addressed. Organisational complexity is shown to increase the complexity of the supply chain design task. Furthermore, organisational complexity contributes to a network of widely distributed and loosely coupled relations between the actors critical for the execution of supply chain design changes. This reduces the possibility for learning and development of lateral relations supporting the complex task of supply chain design. The results thus reveal how organisational design is a significant factor for the successful implementation of changes in supply chain design.

DANSK RESUME

Virksomheder tilpasser løbende deres forsyningskæde for at imødekomme omkostningsoptimering, markedsåbninger eller -nedgang. Det er således ikke usædvanligt, at nyheder i dagspressen omhandler virksomheder, som gennemgår større strukturelle ændringer i deres forsyningskæde. Ofte med en positiv eller negativ vinkling, afhængig af indvirkningen på lokalbeskæftigelse og investeringer. Ligeledes har den videnskabelige forskning adresseret mange aspekter af designet af globale forsyningskæder. Dette inkluderer f.eks. matematiske modeller for det optimale design af forsyningskæden, modeller for sammensætningen af proceskapabiliteter og produktkrav eller styringsmodeller for samspillet mellem aktører. På trods af vigtigheden for den enkelte virksomhedskonkurrencekraft, den samfundsmæssige betydning og den omfattende forskning, så er ændringer af forsyningskædens design ofte forbundet med væsentlige afledte problemer og urealiserede gevinster, som udfordrer det oprindelige rationale for de gennemførte ændringer. Dette ses i form af urealiserede omkostningsreduktioner, øgede koordineringsomkostninger, kvalitetsproblemer, eller manglende fleksibilitet. Den eksisterende forskning har ikke i væsentligt omfang beskæftiget sig med, hvordan den enkelte beslutning, som former forsyningskædens design udfolder sig, og hvad der påvirker effektiviteten af sådanne beslutningsprocesser. Derved er der også et ringe udgangspunkt for at forbedre praksis, og reducere de virksomheds- og samfundsøkonomiske konsekvenser af fejlagtige beslutninger. Denne afhandling forsøger at adressere disse udfordringer, ved at undersøge (1) hvordan beslutninger omkring forsyningskædens design udfolder sig og beslutningsprocessens indvirkning på realiserede ændringer i forsyningskædens design, (2) hvordan det analytiske grundlag for sådanne komplekse beslutninger kan forbedres, og (3) hvordan organisatorisk design påvirker evnen til at beslutte og gennemføre ændringer i forsyningskædens design. Disse spørgsmål adresseres i tæt samspil med en verdensførende producent af komplekse og kapitalintensive produkter. Parallelt med skabelsen af ny viden, er det således også formålet at bidrage til udviklingen af virksomhedens evne til at understøtte beslutninger om forsyningskædedesign.

Afhandlingens resultater dækker over tre dele, repræsenteret ved de tre forskningsspørgsmål. Indledningsvis afdækkes hvordan kompleksiteten af forsyningskæden og kompleksiteten af forandringen af forsyningskæden påvirker beslutningsprocesser og de realiserede forandringer. Resultaterne viser hvordan en stærk afhængighed af en finansiel vurdering af den enkeltstående ændring i forsyningskæden, kombineret med lav synlighed af den marginale omkostning ved stigende kompleksitet, bidrager til stigende kompleksitet af forsyningskæden og derved udgør en barriere for gennemførsel af strategiske ændringer. Yderligere, vises det hvordan gabet mellem de forventede og realiserede resultater af en ændring i forsyningskæden påvirkes af forsyningskædens karakteristika og den tilførte ledelsesopmærksomhed. Derved påvises adfærdsmæssige konsekvenser af

kompleksitet og ledelsesopmærksomhed, som fremtidig forskning bør indarbejde. Resultaterne peger yderligere på ineffektive beslutninger grundet: begrænset systematik i analysen af alternative forsyningskæder, manglende kvantificering af system dynamikker, og begrænset fokus på usikkerheder og sårbarheder.

Denne indsigt danner udgangspunkt for anden del af afhandlingen, som adresserer forbedring af det analytiske grundlag for beslutninger omkring forsyningskædens design gennem en række interventioner, som har haft til formål at forbedre praksis i den industrielle virksomhed. Her udvikles, testes og analyseres en række modeller og metoder til beslutningsunderstøttelse. Dette inkluderer en konceptuel model og proces for en systematisk opstilling og analyse af alternative forsyningskæder. For at understøtte afgrænsningen og nedbrydningen af beslutningerne for forsyningskædens design, introduceres en ratio mellem de to aktivtyper i forsyningskæden: produktionsudstyr og varer. Gennem en matematisk planlægningsmodel, som spænder strategiske og taktiske niveauer, vises det, at rationen er indikativ for hvornår signifikante interaktioner vedrørende lagerudvikling og produktionsplanlægning skal indtænkes i forsyningskædens design. Beslutninger, der både i praksis og i den eksisterende litteraturer normalvis håndteres separat. Modellen udvides yderligere til at kvantificere værdien af volumenfleksibilitet ved ændring af forsyningskædens design, for på den måde at reducere afhængigheden af individuelle ledelsesvurderinger. Dette arbejde afspejler således også, at en af de væsentligste udfordringer vedrørende designet af forsyningskæden, er evnen til at forudsige forsyningskædens systemadfærd, f.eks. opbygningen af lager, og sammenholde denne systemadfærd med andre direkte omkostninger, såsom indkøbspris eller lønomkostninger. Her påvises potentialet i at analysere store mængder operationelle data, for at understøtte decentrale beslutningstagere i at vurderer systemindvirkningen ved ændringer i forsyningskæden. Slutteligt, introduceres en metodik til at vurdere og sammenholde forsyningskædens sårbarhed med dennes omkostninger.

I den tredje og sidste del af afhandlingen, adresseres samspillet med den organisatoriske kompleksitet, som omgiver opgaven med at ændre forsyningskædens design. Organisatorisk kompleksitet øger kompleksiteten af opgaven med at ændre forsyningskædens design. Yderligere, bidrager den organisatoriske kompleksitet til mere vidtforgrenede relationer mellem de aktører, der er centrale for at gennemføre ændringer i forsyningskæden. Herved reduceres muligheden for læring og opbygningen af stærke gentagne relationer for at løfte den komplekse opgave med at ændre forsyningskædens design. Derved fremhæves det, hvordan organisatorisk design er en væsentlig faktor for succesfuld gennemførelse af ændringer i virksomhedens forsyningskæde.

PREFACE

The PhD dissertation builds on an Industrial PhD conducted with a global manufacturer of capital-intensive goods from 2015 to 2018. In this way, the thesis has a two-fold objective to advance and contribute to practice within the industrial partner and advance current knowledge within the field of supply chain design.

This collaboration brought me close to the epicentre of decision-making in a globally leading firm while collaborating across academia and industry. I am indeed grateful for the opportunity to embark on such a challenging and rewarding journey on a topic of such importance for both industry and society.

The dissertation builds on seven papers, of which some are published in international journals, such as *International Journal of Physical Distribution and Logistics Management,* or as a book chapter. Other papers have been presented at conferences or are under review. Thus, this thesis, do not reflect a full stop, but rather a comma in a continued journey towards advancing the understanding of supply chain design.

This dissertation had not been possible, without the strong support from the case company, who have provided an excellent foundation for my research, and Center for Industrial Production at Aalborg University, providing the base for reflection, critical thinking and academic discussion. Indeed, thank you to all colleagues at the case company and Center for Industrial Production for your support and contribution to the project. Especially my supervisor Brian Vejrum Wæhrens has been a strong support to arrive at the current stage. I would also like to thank the colleagues at Centre of International Manufacturing, at the Institute for Manufacturing, Cambridge University, for their warm welcome during my research stay.

Finally, I owe sincere thanks to friends, family and my better half. Your support have been instrumental for me to complete this journey.

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CHAPTER 1. INTRODUCTION

Faced by fast-moving markets, changing customer preferences, rapid competition, technological innovation, uncertain business environments and unexpected disruptive events, an otherwise strong performing supply chain can quickly turn into the Achilles heel of the manufacturing firm. In response to such challenges and changing conditions, manufacturing firms continuously strive to redesign their supply chain to keep up with competitive pressures and accessing new markets. In doing this, the firm raises fundamental questions such as:

- What should be made in-house and what should be sourced from the market?
- Should suppliers be involved in the design and development of new products, and to what extent?
- Where should production sites be located and which products should be produced at which location?
- Who and how many suppliers to collaborate with?
- How to best distribute products to customers?

These questions are interlinked and determine the frame for the future operational performance of the supply chain, and its possibility to strive under uncertainty. Denoting decisions regarding the location, ownership, and linkages between the physical nodes in the supply chain, the importance of supply chain design is evident. However, to accurately predict the future performance in effective and efficient decision-making processes to reach an ‘optimal’ supply chain design is riddled with difficulty.

The possibility of capturing performance improvements through the deliberate redesign of the supply chain remain highly sought by, but it is no simple endeavour to realise such performance improvement. This is witnessed by the numerous managers who have experienced hidden cost following the outsourcing or offshoring of production, and exemplified by Boeing’s struggle to redesign its supply chain for the Dreamliner. Indeed, there is a need, both in practice and academia for better understanding how supply chain design decisions unfold and leverage this understanding for improving supply chain design decision-making.

Although supply chain design has received ample attention for several decades, there remains a limited understanding of how supply chain design decisions unfold, what determines the effectiveness of supply chain design decision-making, and how to organise such decision-making processes. Critical questions to answer, to improve industrial practice and advance managerial relevant research within supply chain design.

1.1. RESEARCH MOTIVATION

Existing literature on supply chain design can broadly be grouped into outcome studies, often large-scale surveys linking specific supply chain design changes, e.g. outsourcing or offshoring, to realized performance differences (Johansson & Olhager, 2018; Stentoft, Mikkelsen, Jensen, & Rajkumar, 2018); Process studies, introducing conceptual models and procedures for assessing and implementing supply chain design changes (Momme, 2002; Marshall, Ambrose, McIvor, & Lamming, 2015; Fredriksson, Wänström, & Medbo, 2014); Modelling papers, focused on developing increasingly sophisticated models for identifying an optimal supply chain design (Klibi, Martel, & Guitouni, 2010; Meixell & Gargeya, 2005; Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011).

Despite the decision-making process being critical for the resulting supply chain design and thereby firm performance, the decision-making process itself and its behavioural context have received limited attention in a supply chain context (Manuj & Sahin, 2011; Mantel, Tatikonda, & Liao, 2006). This is especially true for decision-making relating to strategic aspects of supply chain management, such as supply chain design decisions, which have received limited attention in existing supply chain research (Schorsch, Wallenburg, & Wieland, 2017). Few exceptions relate to behavioural aspects of supply chain design decision-making. Mantel et al. (2006) investigated how core competency, strategic vulnerability, and information source formality influence supply managers' evaluation of make versus buy. However, relying on a mail survey for a controlled experiment, it offered limited insight into understanding how information search and analysis is conducted, or how the organisational frame influenced decision-making. Wouters et al. (2009), utilising a survey study, investigated actual sourcing decisions within new product development projects. Their results show the importance of monetary quantification of alternatives and decision justification to senior management in reducing the perceived uncertainty of decision-making. Decision justification to senior management was significant in determining the effort put into detailed information gathering by project managers, which thereby contributed to reducing decision uncertainty.

Similarly, it is shown that procedural rationality, *"the extent to which the decision process involves the collection of information relevant to the decision, and the reliance upon analysis of this information in making the choice"* (Dean & Sharfman, 1993, p. 589), improves the decision effectiveness (i.e., realization of expected benefits) of supplier selection decisions (Kaufmann, Kreft, Ehrgott, & Reimann, 2012). However, highly procedural rational decision processes carry an additional cost regarding time and resources for data collection and analysis. This trade-off between decision-making effectiveness and efficiency has not been explored. Neither is it clear that procedural rationality would have a similar effect for more complex decisions, such as supply chain design changes jointly considering, e.g., supplier selection, production location, and capital investments. Supplier selection decisions usually follow standardised and repetitive workflows, enabling procedural rationality

(Kaufmann, Kreft, Ehrgott, & Reimann, 2012). However, complex supply chain design changes might not adhere to predetermined workflows, thereby diminishing the value of procedural rationality. Indeed, supply chain complexity has been identified by practitioners and academics as one of the most critical barriers to supply chain redesign (Krægpøth, Stentoft, & Jensen, 2017), and several authors call for investigating how complexity influences and interacts with supply chain decision-making (Schorsch, Wallenburg, & Wieland, 2017; Manuj & Sahin, 2011; Bozarth, Warsing, Flynn, & Flynn, 2009; Dittfeld, Scholten, & Van Donk, 2018).

Contemporary research substantiates the need for improving the understanding and practice of complex supply chain design decision-making. Grey et al. (2013) point to erroneous managerial assessment at the point of decision-making as a significant explanation for unrealised performance benefits and therefore subsequent decisions to re-shore or insource. Gylling et al. (2015) find such explanations in their analysis of a Finnish bicycle manufacturer reshoring production. In adjacent research, within IT-services, Larsen et al. (2013) empirically show substantial cost estimation errors in the offshoring and outsourcing of activities, with more than 20% of outsourcing and offshoring decisions resulting in more than a 10% perceived gap between expected and realised cost performance. Furthermore, Larsen and colleagues demonstrate a significant relationship between the complexity of the outsourced activities and the accuracy of cost estimations and calls for more research on how complexity influences estimation ability.

Such a link between complexity and estimation ability suggests escalating challenges for the effectiveness of supply chain design decision-making, as firms become increasingly complex in response to increasingly complex and competitive environments (Ashmos, Duchon, & McDaniel Jr, 2000; Bozarth, Warsing, Flynn, & Flynn, 2009). Boeings Dreamliner project is one such example of how firms are seeking increasingly complex supply chain designs and extensive transformations of existing supply chain designs, and that such changes do not always deliver the expected payoff. Contract manufacturing, outsourcing, offshoring, back-sourcing, 3rd party logistics providers, black-box sourcing, and tech-transfer are all examples of the types of changes and configurations being pursued by supply chain managers to improve their supply chain design.

While the topic of supply chain design decision-making has received only limited attention in existing research, several trends are pointing to the increased importance and difficulty of the supply chain design task. These trends and their impact on supply chain design decision-making is summarised in Table 1.1. These motivate both the practical and academic interest in researching and improving supply chain design decision-making.

Table 1.1: Trends and challenges for supply chain design decision-making

Trend	Impact on supply chain design decision-making	Link to literature
Increasing global competition	• Need to continuously ensure an optimal supply chain design to remain competitive. • Increased need for accuracy in decision-making to avoid hidden costs eroding competitiveness.	(Gylling, Heikkilä, Jussila, & Saarinen, 2015; Larsen, Manning, & Pedersen, 2013)
Expansion of solution space for supply chain design.	• Seeking an increasingly complex supply chain design to cope with competitive pressure. • Increase in the analytical effort required to select between complex supply chain design alternatives.	(Ashmos, Duchon, & McDaniel Jr, 2000; Krægpøth, Stentoft, & Jensen, 2017)
Increasing supply chain complexity	• Increased difficulty in identifying an optimal solution and predicting future performance.	(Larsen, Manning, & Pedersen, 2013; Krægpøth, Stentoft, & Jensen, 2017; Bozarth, Warsing, Flynn, & Flynn, 2009; Manuj & Sahin, 2011)
Increased volatility in the environment of the supply chain	• Increased difficulty in predicting future performance when subject to uncertainty. • Need for different supply chain design criteria. • Increased frequency of supply chain design changes.	(Christopher & Peck, 2004; Christopher & Holweg, 2017; Christopher & Holweg, 2011)

1.2. EMPIRICAL MOTIVATION

With this PhD study being conducted as an industrial PhD project, it rests on a strong empirical motivation. The case company is a world-leading original equipment manufacturer (OEM) of complex, capital-intensive goods. The company manages a global and complex supply chain, operating more than 20 factories across four continents and buying more than 10,000 parts from thousands of different suppliers located in more than 40 different countries.

The proliferation of product offerings, expansion of the manufacturing network and introduction of new products has increased supply chain complexity, as depicted in

Figure 1.1. During a five-year period, the company has faced a 62% increase in the number of supplier-item-plant relations.[1]

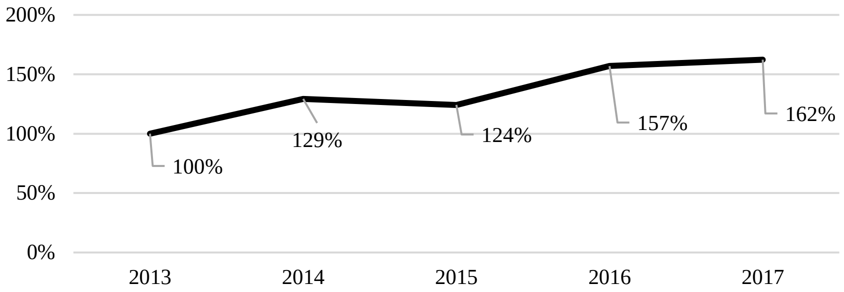

Figure 1.1: Development of supplier-item-factory relations in the supply chain. Index 100%=2013.

The increase in complexity has been met by increased concern from senior management and the initiation of strategic initiatives to redesign the supply chain to reduce complexity and better align the supply chain design to competitive priorities. From senior management, there were clear expectations that redesign of the supply chain would offer a lower total cost, increased flexibility, and reduced supply chain complexity.

However, opposing forces facing the OEM’s complex supply chain increase the difficulty of redesigning the supply chain. Downstream, demand from individual markets is subject to uncertainty from macroeconomic conditions, politically decided subsidy schemes, subject to regulatory changes, and large-scale auction-based selling resulting in a discrete and uncertain demand pattern. Combined with local content requirements for the establishment of local supply chains and manufacturing activities. These conditions call for a foot-loose supply chain (Ferdows, Vereecke, & De Meyer, 2016) that combines the ability to react to market bust and booms, with the ability to establish local production in compliance with the requirements of individual markets. Upstream, sensitive product and process tolerances require a long time for qualification, test and validation. Combined with closely knitted relationships and specialised capabilities, this oppositely calls for a rooted supply base and manufacturing network. At the same time, competitive pressure and short new product

[1] Being the activity driver of both strategic purchasing activities (e.g., supplier identification, appointment and negotiation), operational buying (e.g., update forecast, issue purchase orders, update expected arrival data), warehouse (e.g., goods received, quality inspections and shelfing) and finance (e.g., process invoice and payment), the number of supplier-item-plan relations helps to underpin a significant increase in overall supply chain complexity.

introduction cycles create significant pressure to both continuously reduce cost in the supply chain and design and introduce new products.

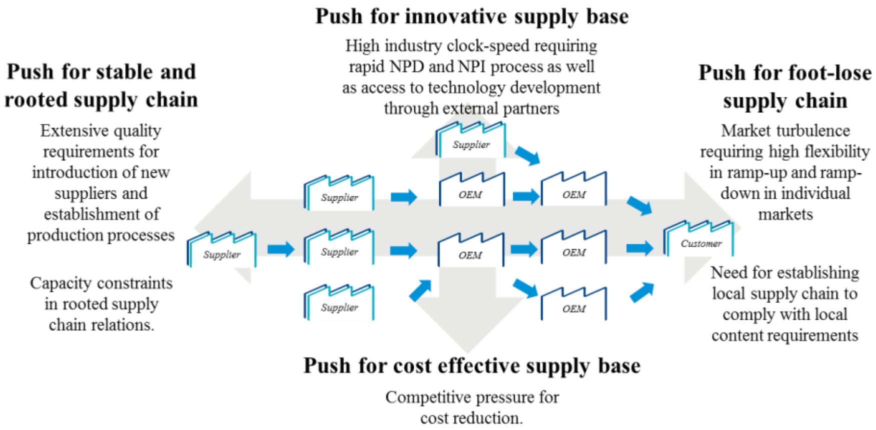

Figure 1.2: Conflicting forces acting on the supply chain

Symptomatic of these opposing forces illustrated in Figure 1.2 is the concern of different stakeholder coalitions, with varying perceptions of competitive priorities and worldviews. Sales would, for example, have immediate concerns regarding the match of the supply chain footprint with customers' locations and compliance with requirements for local production, whereas manufacturing would be concerned with ensuring efficient production processes and capacity utilisation, and engineering would be concerned with leveraging suppliers' capabilities for new product development. Supply chain design decisions in such a complex environment would thus be riddled with difficulty and conflicting objectives, whereas shortening market openings and increasing competitive pressure calls for both *fast* and *accurate* decision-making to enable the OEM to respond to market opportunities, while still ensuring a cost-competitive supply chain design. Effective supply chain design decision-making requires decision-makers to be able to answer questions such as:

- How is complexity reduction or improvement in volume flexibility to be valued against a direct product cost increase?
- Who should drive the supply chain design decision process?
- Should supply chain design decisions be conducted decentralised within the line organisation, leveraging and enabling close alignment with the functions impacted, or should centralised and specialised teams run them to ensure a global overview?

The core hypothesis underpinning the thesis is that it is possible to realign these forces (Figure 1.2) and reduce the tension in the supply chain through a deliberate and model-based redesign of the supply chain. Achieving this requires not only appropriate tools and methods underpinning supply chain design decision-making, but also an organisational design, enabling efficient and effective supply chain design decision-making and implementation of changes. In this way, this PhD study is intended to offer industrial insight into the development of *a supply chain design capability*. This is a broader perspective on the offshoring capability (Mihalache & Mihalache, 2016) or the make-buy capability (Fine & Whitney, 2002).

1.3. RESEARCH OBJECTIVE

Building on the outlined industrial problem and the research gap, this industrial PhD dissertation seeks to contribute to both practice and research. The industrial objective is to *improve supply chain design decision-making within the OEM*. This is complemented by answering three research questions, making distinct, but complementary contributions to extant literature:

RQ1: How are supply chain design decision-making processes linked to realised supply chain design changes?
RQ2: How can the analytical foundation for supply chain design decisions be improved?
RQ3: How does organisational design influence the supply chain design task?

The research questions build on the recognition that supply chain design decisions are not made by "a firm" or an all-knowing and rational Homo Economicus, but rather nested within an organisation populated by boundedly rational individuals (Cyert & March, 1963; Simon, 1955). The research thereby diverts from traditional rationalist perspectives employed when researching supply chain design decision-making (Mantel, Tatikonda, & Liao, 2006; Ketokivi, Turkulainen, Seppal, Rouvinen, & Ali-Yrkko, 2017; Melo, Nickel, & Saldanha-da-Gama, 2009; Mihalache & Mihalache, 2016).

RQ1 investigates how supply chain design decision-making processes unfold by taking the perspective of the individuals involved in the actual decision-making, to investigate how the practice of decision-making is linked to the realised outcome. Addressing RQ1 advances the understanding of how supply chain design decision-making unfolds in a context of complex manufacturing supply chains, a critical step towards improving decision-making, and addresses the limited knowledge of the role of complexity in supply chain decision-making.

Addressing RQ1 by investigating how decision-making unfolds creates an understanding for subsequently improving the analytical foundation underpinning complex supply chain design decisions. On the basis that supply chain design decision-making is a somewhat formalised decision process, with a certain level of procedural rationality (Dean & Sharfman, 1993), RQ2 addresses how the analytical foundation underpinning supply chain design decision-making can improve decision-making effectiveness and efficiency. The former is understood as the comprehensiveness and accuracy of predictions on future performance, and the latter as the time and resources required for decision-making. Combining the advancement of the analytical foundation with the behavioural context of decision-making acts as an important element in actually advancing managerial decision-making, rather than contributing to the development of increasingly sophisticated mathematical models, with limited contribution or connection to actual decision-making processes (Ferdows, Vereecke, & De Meyer, 2016).

RQ3 seeks to address the fact that the existing research offers limited guidance on how to organise around the supply chain design task (Moschuris, 2008; Ferdows, 2016). Investigating how the task of changing the design of the supply chain supply is related to organisational design offers insight on how to organise the supply chain design task.

The thesis builds on a progression from first linking decision-making to realised outcomes with RQ1. Building on this understanding, RQ2 seeks to improve the analytical foundation underpinning supply chain design decision-making, while RQ3 offers insight into the organisational design surrounding the supply chain redesign task. This scope and progression is illustrated in Figure 1.3. In the research scope, there is a specific focus on the decision process and outcome, while the implementation process receives less attention. There are two reasons for this focus. First, the decision-making process acts as a formal commitment of time and resources to a decided course of action. This commitment is often pursued beyond the stage where it is evident that the course of action is no longer suitable (Marshall, Ambrose, McIvor, & Lamming, 2015). Thus, while the implementation process is important for the realisation of the decided course of action, and influences the realised outcome through subsequent detailed decision-making (Marshall, Ambrose, McIvor, & Lamming, 2015), it remains important to improve the understanding of how the initial decision-making, which initiates an escalation of resource commitments, is linked to the realised outcome. Second, substantial literature already addresses the "implementation" stage of supply chain design (Momme, 2002; Marshall, Ambrose, McIvor, & Lamming, 2015; Fredriksson, Wänström, & Medbo, 2014), while the supply chain design decision-making process has received limited attention (Schorsch, Wallenburg, & Wieland, 2017; Manuj & Sahin, 2011; Larsen, Manning, & Pedersen, 2013).

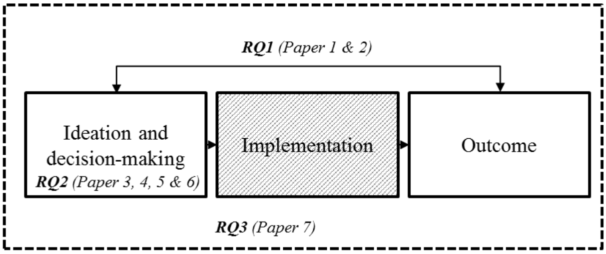

Figure 1.3: Scope in the investigation of supply chain redesign.

1.4. THESIS OUTLINE

The thesis builds on the following structure. Chapter 2 introduces the theoretical background underpinning this research. Next, Chapter 3 presents and argues for the research design to address the identified research objective and three research questions. Chapters 4, 5 and 6 present and elaborate on the thesis findings related to RQ1, RQ2 and RQ3, respectively. Chapter 7 consolidates the discussion of the research questions and concludes the dissertation.

The paper builds on seven publications addressing the research question as depicted in Figure 1.3. These papers are listed below:

1. **Asmussen, J.N.**, Kristensen, J. and Wæhrens, B.V. (2017), The Link Between Supply Chain Design Decision-Making and Supply Chain Complexity: An Embedded Case Study, *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing,* Lödding H., Riedel R., Thoben K.D., von Cieminski, G. and Kiritsis, D. (eds), Hamburg, Germany, pp.. 11-19.
2. **Asmussen, J.N.**, Kristensen, J. and Wæhrens, B.V. (2018), Cost estimation accuracy in supply chain design: The role of decision-making complexity and management attention, *International Journal of Physical Distribution & Logistics Management*, Vol. 48, No. 10.
3. **Asmussen, J.N.**, Kristensen, J. and Wæhrens, B.V. (2016), Supply Chain Costing: Beslutningsunderstøttelse for nye forsyningskonstellationer, In: *Produktion og styring: Perspektiver på økonomistyringen*¸ Bukh, P.N. and Kristensen, T.B. (eds), Djøf/Jurist- og Økonomforbundet, pp. 259-275. **[in Danish]**
4. **Asmussen, J.N.**, K., Kristensen, J., Steger-Jensen, and Wæhrens, B. V. (2018). When to integrate strategic and tactical decisions? Introduction of an asset/inventory ratio guiding fit for purpose production planning. *International Journal of Physical Distribution & Logistics Management*, Vol, 48 No. 5, pp. 545-568.

5. **Asmussen, J.N.**, Kristensen, J. and Wæhrens, B.V. (2018), Outsourcing of production: The value of volume flexibility, *LogForum*, Vol. 14, No. 4, pp. 73-83.
6. **Asmussen, J.N.**, Kinra, A., Uhre, M., and Lund, R. (2016). An effect-oriented approach to assessing supply side vulnerability in global supply chains. In *Nineteenth International Working Seminar on Production Economics*.
7. **Asmussen, J. N.**, Kristensen, J., & Wæhrens, B., Organizing for supply chain redesign: The role of organizational complexity (*Submitted for Journal of Purchasing and Supply Management*)

These papers reflect the wide theoretical and practical domain that supply chain design spans. While the individual papers carry their own justification and contribution, this thesis builds on these papers to improve the theoretical understanding of supply chain design decision-making, and the practical ability to undertake the redesign of complex manufacturing supply chains.

Another six industry-oriented and conference proceedings listed in Table 1.2 have been authored or co-authored. These publications further substantiate the academic and practice-oriented knowledge dissemination but are not a part of the final thesis.

Table 1.2: Supporting knowledge dissemination

Authors	Title	Type of dissemination
(**Asmussen** & Wæhrens, The effect of resilient supply chain strategies on New Product Introduction capabilities: A case study from the R&D intensive renewable energy industry, 2015)	The effect of resilient supply chain strategies on New Product Introduction capabilities: A case study from the R&D intensive renewable energy industry.	*22nd International EurOMA Conference*.
(**Asmussen**, Wæhrens, & Kristensen, 2015)	”Fra risikostyring til resiliens i forsyningskæden”	Practice (Effektivitet, Vol. 4, pp. 8-12.)
(**Asmussen** J. , Kristensen, Wæhrens, & Toldbod, 2016)	*Supply Chain Costing*	Practitioners workbook
(**Asmussen** J. , Kristensen, Kristensen, & Wæhrens, 2016)	Comparing Cost Of New Supply Chain Designs Under Uncertainty: An Empirical Study Of Challenges And New Opportunities	*5th POMS World Conference*
(**Asmussen**, Steger-Jensen, Kristensen, & Wæhrens, 2017)	Integrated Capacity and Production Planning: Including supply chain flexibility and capital investments	*NOFOMA 2017 Conference*
(Kristensen, **Asmussen**, & Wæhrens, 2017)	The link between the use of advanced planning and scheduling (APS) modules and factory context	Industrial Engineering and Engineering Management (IEEM), 2017 IEEE International Conference

CHAPTER 2. THEORETICAL BACKGROUND

This chapter starts by defining supply chain design decisions. Subsequently, three literature streams, *supply chain resilience*, *operational modelling* and *cost accounting*, which inform supply chain design, are reviewed and synthesised. These three perspectives build on an analytical and systems perspective on the supply chain design problem, where the role of the actor (decision-maker) is mostly absent. To enable a more nuanced understanding of the supply chain design decision problem, the concepts of supply chain complexity and supply chain decision-making complexity are introduced. These two concepts, building on decision-making theory, are useful for embracing the role of the boundedly rational decision-maker, who may or may not rely on a sophisticated analytical foundation when making supply chain design decisions. Two meta-theories, the behavioural theory of the firm (BTF) and information processing view (IPV), are introduced to offer an overarching theoretical frame for researching supply chain design decision-making.

2.1. SUPPLY CHAIN DESIGN DECISIONS

Meixell and Gargeya (2005, p. 532) define supply chain design decisions as *"decisions regarding the number and location of production facilities, the amount of capacity at each facility, the assignment of each market region to one or more locations, and supplier selection for sub-assemblies, components and materials."* This definition is further augmented by Carvalho et al. (2011, p. 330): "*SC design is related to the definition of the structure of the chain, i.e., the sequential links between different sourcing, production and distribution activities or processes, leaving the planning and control process out of its scope."*

Changing the supply chain design thus reflects a multitude of opportunities pursued by manufacturers to optimise operations across global networks, e.g., outsourcing and offshoring (Gylling, Heikkilä, Jussila, & Saarinen, 2015), reconfiguring manufacturing networks (Ferdows, Vereecke, & De Meyer, Delayering the global production network into congruent subnetworks, 2016; Shi & Gregory, 2005), or reshoring and insourcing (Ellram, Tate, & Petersen, 2013). In this thesis, the focus is on supply chain design decision-making, as an umbrella for a decision problem, rather than a specific solution (e.g., outsourcing). Reflecting that firms frequently engage in, e.g. offshoring, reshoring outsourcing, and insourcing simultaneously (Johansson & Olhager, 2018), and that such alternatives are evaluated against each other. It is thus in better congruence with industrial practice to research the supply chain design decision process, rather than the 'location decision process' (Ketokivi, Turkulainen, Seppal, Rouvinen, & Ali-Yrkko, 2017), 'make-buy decision process' (Mantel, Tatikonda, & Liao, 2006) or 'supplier selection process' (Kaufmann, Kreft, Ehrgott, & Reimann, 2012), as these are interlinked and occur in parallel as part of determining the supply chain design.

Supply chain design decisions are non-repetitive, they span multiple stakeholders, and relate to discrete changes in the configuration of material and information flows. Supply chain design decisions thereby also influence the structure for functions such as procurement, production, warehousing, transport, planning (Klibi, Martel, & Guitouni, 2010), R&D and engineering activities (Handfield & Lawson, 2007). It is therefore evident that the performance ramifications of supply chain design decisions go beyond direct product cost, impacting coordination (MacCarthy & Atthirawong, 2003; Schulze, Seuring, & Ewering, 2012), inventory build-up and service level (Meixell & Gargeya, 2005), as well as the exposure to and ability to cope with uncertainty (Christopher & Holweg, 2011; Klibi, Martel, & Guitouni, 2010; Christopher & Peck, Building the Resilient Supply Chain, 2004).

The assessment and prediction of the expected outcome of a supply chain design change is a critical step in the design process (Fredriksson & Jonsson, 2009). The supply chain's importance for operational performance and the low reversibility of decisions stress the importance of accurate ex-ante performance predictions (Klibi, Martel, & Guitouni, 2010). In the next section, existing literature is reviewed and synthesised to understand how the research has addressed the question of predicting future supply chain performance and informing supply chain design decision-making.

2.2. ANALYTICAL FOUNDATION FOR SUPPLY CHAIN DESIGN

The following section synthesises existing approaches to supply chain design and outlines how the 'practice' of determining and evaluating supply chain designs has been addressed in the existing literature. The literature can broadly be classified into three perspectives on the analytical foundation for the supply chain design problem: (1) supply chain resilience, (2) operational modelling, and (3) cost accounting.

These streams of literature are introduced and subsequently analysed regarding their complementarity in offering a comprehensive analytical foundation for supply chain design decision-making. The purpose is not to provide an exhaustive review of each stream of literature, but to establish an understanding of how the streams of research are positioned to contribute to supply chain design decision-making.

2.2.1. SUPPLY CHAIN RESILIENCE

Faced with increasing turbulence and disruptions, Pettit, Fiksel and Croxton (2010) identify three capabilities characterising the resilient supply chain; the capability to (1) prevent a disruption, (2) mitigate the detrimental effects of disruption, or (3) adopt a new configuration following a disruption. In line with this, Wieland and Wallenburg (2013) define supply chain resilience through the two concepts of, robustness and agility. Robustness relates to the ability of the supply chain to *"resist change without adapting its initial stable configuration"* (Wieland & Wallenburg, 2012, p. 890) and, thus, how to make the supply chain proactively cope with change. Agility relates to the ability to adapt the supply chain ex-post a disruption, leading to a reactive approach to changes. Agility is therefore understood as *“the ability of a supply chain to rapidly respond to change by adapting its initial stable configuration”* (Wieland & Wallenburg, 2012, p. 890). Achieving robustness and agility in the supply chain is closely associated with the design of the supply chain, and the criteria used for designing the supply chain (Christopher & Holweg, 2011).

Carvalho et al. (2011) emphasise that *‘Resilience should be designed-in, through the management of SC design characteristics”* (Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011, p. 331). Several supply chain design strategies for increasing supply chain resilience have been brought forward in the literature, such as postponement (Tang, 2006) or asset sharing (Christopher & Holweg, 2011) for increasing agility. Meanwhile, *make-and-buy* and *strategic inventory* (Tang, 2006) are examples of strategies increasing robustness. Other supply chain design strategies for increasing supply chain resilience include *outsourcing* and *dual sourcing,* which are suggested for increasing agility and robustness, respectively (Christopher & Peck, 2004; Christopher & Holweg, 2011; Pettit, Fiksel, & Croxton, 2010; Tang C. , 2006).

Both dimensions of supply chain resilience, i.e., robustness and agility, require ex-ante investments enacted during supply chain design decisions. The focal firm may choose to invest in strategic safety stock to increase robustness against a supplier disruption (Christopher & Holweg, 2011), which leads to an observable change in the form of higher inventory levels and a higher cost. Reactive approaches, such as sourcing flexibility using standard components in product design (Wieland & Wallenburg, 2013), similarly require an initial investment, but the impact can only be seen ex-post a disruption when the flexibility is utilized. Flexibility thereby resembles *real options* (de Treville & Trigeorgis, 2010). A real option provides the possibility, but not the obligation, to react to changes, e.g., by operating a supply chain with multiple suppliers or multiple transport modes. The real option carries an initial cost (e.g., pre-approving an additional supplier), as well as an execution cost (e.g., price premium from using the second source), which enables the firm to introduce a new stable and effective configuration following a significant disruption. This makes the managerial assessment and valuation of design strategies for robustness and agility challenging, as they relate to a capability that might not be exercised (Jack & Raturi, 2002).

As resilience requires an upfront investment and cost, it should be justified by the vulnerability and uncertainty faced by the supply chain to avoid eroding profit margins (Pettit, Fiksel, & Croxton, 2010). Balancing these dimensions in the design of the supply chain requires a holistic understanding of the influence of specific strategies for increasing resilience both upstream and downstream the supply chain, as well as vulnerabilities in the supply chain design and uncertainties faced.

Decision-makers need to acquire an understanding of uncertainty in the external environment and link this uncertainty to the future behaviour of the supply chain, to arrive at a balance between uncertainty and resilience in the supply chain design. However, the realisation of resilient supply chain structures is not straightforward, as existing approaches for comparing the performance of a given supply chain design, such as Net Present Value, entail a static view not reflecting system behaviour or uncertainty. Such a calculation, therefore, does not justify building agility and robustness into the supply chain design (Christopher & Holweg, 2011).

2.2.2. OPERATIONAL MODELLING:

Mathematical programming and simulation are well suited for capturing the system behaviour of interconnected and stochastic systems, such as supply chains. For the supply chain design problem, mathematical models are typically formulated to provide an optimal solution minimising the cost or maximising the profit of a supply chain design (Meixell & Gargeya, 2005) evaluated on supply chain performance metrics and associated cost. Performance metrics and costs include capacity utilisation and capacity cost, inventory levels and inventory holding cost, as well as service level and backorder cost (Santoso, Ahmed, Goetschalckx, & Shapiro, 2005; Liu & Papageorgiou, 2013; Shapiro, 1999). Meixell and Gargeya (2005, p. 536) identify the most common decision variables to be *"facility selection, production/shipment quantities, and supplier selection."* Additional decision variables that are considered include capacity expansion (Lowe, Wendell, & Hu, 2002), transfer prices and transport mode (Vidal & Goetschalckx, 2001), or the shift of production between facilitates (Dasu & de la Torre, 1997).

In recent years, mathematical models have been extended to incorporate uncertainties in decision models by applying sensitivity analyses and scenarios (Baghali, Rezapour, & Farahani, 2013; Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011; Georgiadis, Tsiakis, Longinidis, & Sofioglou, 2011). In this way, mathematical programming and simulation are useful for linking uncertainties using scenarios and stochastic variables to a performance impact (Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011).

In summary, the mathematical modelling literature addressing the supply chain design problem is characterised by a perspective on the supply chain design problem as one joint decision (Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011; Melo, Nickel, & Saldanha-da-Gama, 2009; Meixell & Gargeya, 2005). The resulting decision is translated to a single objective function, e.g., cost, or various performance criteria weighted against each other in a goal-programming approach, thereby assuming that significant and relevant performance indicators can be meaningfully quantified, weighted and compared (Melo, Nickel, & Saldanha-da-Gama, 2009; Meixell & Gargeya, 2005).

Despite the centralised and global nature of the supply chain design model, the supply chain design problem is often partitioned based on hierarchical and functional levels, to enable realisable computation time and solve problems for optimality. Inventory levels are therefore typically not considered as a part of the supply chain design decision since inventory decisions reflect short-term decision-making that is subsequently optimised within the determined supply chain structure (Meixell & Gargeya, 2005). However, it is clear that dependencies exist between, e.g., the location of production relative to customers and resulting inventory levels, or the level of capacity in the supply chain and inventory levels. Ignoring such interactions between hierarchical levels introduces the risk of suboptimal decision-making (Baghali, Rezapour, & Farahani, 2013; Melo, Nickel, & Saldanha-da-Gama, 2009).

A further challenge for the useful application of these mathematical models for supply chain design is the reliance of cost parameters, e.g., holding cost or back-ordering cost, treated as exogenously given under which optimality should be found (Cohen, Ho, Ren, & Terwiesch, 2003). However, these cost parameters could be considered perceptual, leading to different outcomes dependent on departmental worldviews (Niranjan, Rao, Sengupta, & Wagner, 2014). For example, customer-facing salespeople would emphasise the importance of back-order cost due to their awareness of the negative feedback from customers, whereas logistics managers would emphasise inventory holding cost, due to their awareness of the complications of holding inventory. Diverging departmental views, therefore, pose a challenge for the cross-functional acceptance of supply chain design solutions if input parameters are lacking consensus. Furthermore, cost parameters often draw on simplistic assumptions, for example, if holding cost is assumed to be a percentage of the item cost, but that does not reflect that the cost incurred depends on more than just the cost of the capital invested, but also the storage space consumed, the number of pick and pack activities, and the risk of obsolescence etc. Cost drivers which are dependent on several product characteristics, not only unit cost (Berling, 2008). The successful use of operational modelling, therefore, relies on accurate cost relationships (Shapiro, 2006), as well as information for scenarios or stochastic values for uncertainties.

2.2.3. COST ACCOUNTING:

Cost accounting and its derivatives, e.g., strategic cost management (Anderson & Dekker, 2009), offer a distinct but complementary perspective on the supply chain design problem, leveraging cost information for determining the configuration of value chain activities. Indeed, cost management tools are perceived as an impartial criterion for the evaluation of strategic alternatives (Schulze, Seuring, & Ewering, 2012) and are thereby bound to play an essential role in supply chain design decision-making.

Activity-Based Costing (ABC) as a methodology to allocate indirect expenses to cost objects, such as products, suppliers or customers (Cooper & Kaplan, 1988), and subsequently Time-driven ABC (TD-ABC) (Kaplan & Anderson, 2004), have received substantial interest in relation to supply chain decision-making (Hofmann &

Bosshard, 2017; Everaert, Bruggeman, Sarens, Anderson, & Levant, 2008; Schulze, Seuring, & Ewering, 2012). ABC has been utilised in specific methodologies, such as for the total cost of ownership (Ellram, 1995) or to determine inventory holding cost (Berling, 2008), an essential input factor for operational modelling. ABC has also been leveraged for more systematic analysis of supply chain design by developing ABC models for supply chain management (Schulze, Seuring, & Ewering, 2012). The value of ABC lies in its ability to create an improved understanding of the indirect cost required for the activities involved in sustaining and executing the supply chain, e.g., the cost of managing a supplier relationship or issuing a purchase order. When employed in an inter-company context, this allows for the identification of a cost-optimal location of activities, with a clear link to the profit and loss statement of the firm. In this way, it is possible to offer detailed and accurate cost information for supply chain decision-making, which can be leveraged for improving the supply chain design (Everaert, Bruggeman, Sarens, Anderson, & Levant, 2008).

However, both ABC and TD-ABC remain an ex-post cost allocation (Shapiro, 2006). None of the approaches capture the system behaviour of a supply chain operating under uncertainty, nor does it point to an optimal supply chain design. Indeed, the applications presented in the existing literature suggest supply chain design changes based on analysis of historical cost, with improvements being incremental to the existing design (Schulze, Seuring, & Ewering, 2012; Everaert, Bruggeman, Sarens, Anderson, & Levant, 2008).

2.2.4. SYNTHESIS

The three streams of literature are complementary in informing supply chain design decisions. This is reflected in work seeking to combine the different fields of literature. Operational modelling has been combined with cost accounting (Schulze, Seuring, & Ewering, 2012; Degraeve & Roodhoft, 1998; Degraeve & Roodhooft, 1999; Degraeve, Labro, & Roodhoft, 2005). Similarly, operational modeling has been extended with considerations of supply chain resilience (Georgiadis, Tsiakis, Longinidis, & Sofioglou, 2011; Baghali, Rezapour, & Farahani, 2013; Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011), while no work has been found to link cost accounting with supply chain resilience. Instead, the three streams of literature can be seen to reflect a progression from cost accounting addressing an observable past, i.e., what can be captured through accounting systems and time-estimates, to operational modelling, addressing the behaviour of the supply system, to supply chain resilience addressing the ability to cope in an unknown and uncertain future. This reflects how the three different streams of literature address different questions relevant to supply chain design decision-making, as illustrated in Figure 2.1.

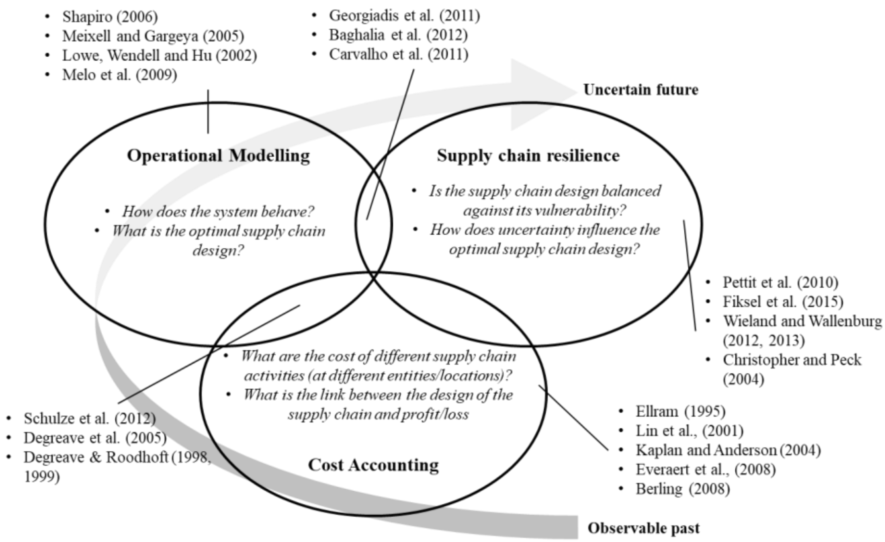

Figure 2.1: Literature streams addressing the analytical foundation for supply chain design decisions.

While each of the three areas has limitations as a decision foundation, there are evident complementarities between the three areas. These complementarities have been synthesised in Table 2.1. The use of cost accounting can provide cost assumptions and cost relationships found in the supply chain. Operational modelling offer suggestions on the optimal configuration of internal resources for operating and sustaining the supply chain, while encapsulating the system behaviour of the supply chain, thereby quantifying the value of real options in the supply chain design, together with the impact of uncertainty.

Table 2.1: Supply chain design decision foundation and their interplay

Literature stream	**Suggested Practice:**	**Contribution to decision making:**	**In need of:**
Supply chain resilience	• Managerial controls (dual sourcing, flexible suppliers, make & buy etc.) • Real Options • Scenarios and sensitivity analysis • Historic fluctuations	• Supply chain design strategies for robustness and agility • Identification of vulnerabilities and uncertainties.	• Operational Modelling • Financial valuation

Operational Modelling	• Mathematical optimisation • Simulation	• Quantification of supply chain performance • Understanding of supply chain system behaviour • Stochastics to assess uncertainties	• Scenarios or values for uncertainties • Accurate Cost Relationships
Cost Accounting	• Standard Group Cost • ABC and TD-ABC	• Cost relationships and cost drivers	• Operational Modelling

While some authors build on industrial cases for the development and testing of their analytical foundation for supply chain design (Schulze, Seuring, & Ewering, 2012; Degraeve & Roodhoft, 1998; Everaert, Bruggeman, Sarens, Anderson, & Levant, 2008; Degraeve, Labro, & Roodhoft, 2005; Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011), the discussion of the broader context for the enactment and application of the analytical foundation in complex decision processes are largely absent. This provides validity to the critique that these contributions are disconnected from the industrial practice of supply chain design decisions (Ferdows, Vereecke, & De Meyer, Delayering the global production network into congruent subnetworks, 2016). To advance the understanding of supply chain design decision-making, and to improve supply chain design practice, it is, therefore, necessary to relate the analytical foundation to the broader theoretical context of supply chain decision-making processes.

2.3. SUPPLY CHAIN DECISION-MAKING AND META THEORIES FOR DECISION-MAKING

Most of the empirical work on supply chain design builds on two theoretical pillars, either the resource-based view (RBV), transaction cost economics (TCE), or a combination (McIvor, 2009; Holcomb & Hitt, 2007; Johansson & Olhager, 2018; Mihalache & Mihalache, 2016). In brief, the resource-based view is concerned with explaining the resulting supply chain design based on relative resource positions, while transaction cost economics is concerned with the selection of proper governance for transactions, typically associated with the potential risk of opportunism. These theoretical lenses have typically been deployed in outcome-based studies (Johansson & Olhager, 2018; Mihalache & Mihalache, 2016), offering limited insight on how decision-makers conduct information search and evaluate decisions resulting in the outcomes predicted by the theoretical lenses. Indeed, a distance to the decision-maker is introduced by assuming how the decision-maker thinks (Ketokivi, Turkulainen, Seppal, Rouvinen, & Ali-Yrkko, 2017), as exemplified by the following quotation: *"According to this perspective* (complementarity between RBV and TCE), *in the decision regarding the strategic outsourcing of production, firms evaluate internally accessed capabilities and those capabilities available externally from intermediate markets, and consider how they might best be integrated to produce the greatest value"* (Holcomb & Hitt, 2007, p. 465). Such behaviour might be assumed if one is viewing supply chain design decisions from afar, in which a unified rational approach for decision-making appears appealing (Schoemaker, 1993, p. 121). However, when zooming in on the decision-making process, a more nuanced picture is required, calling for the application of a different set of theoretical lenses embracing the socio-behavioural aspects of decision-making (Mihalache & Mihalache, 2016).

It is evident that supply chains constitute complex systems, whose performance is influenced in a multifaceted way, with linear changes in one part of the system resulting in non-linear and unpredictable effects in other parts (Dubois, Hulthén, & Pedersen, 2004; Fredriksson & Jonsson, 2009). Such complex interactions increase the difficulty of decision-makers in predicting the performance impact when changing the system. Industry experts and academics, therefore, identify supply chain complexity as one of the most critical barriers for supply chain redesign, due to the difficulty of identifying optimal supply chain design (Krægpøth, Stentoft, & Jensen, 2017). This difficulty of predicting future performance, and the role that the decision-maker constitutes in the supply chain design decision, have only been addressed implicitly in the literature on supply chain design. Although the former section points to significant contributions already made, within an 'analytical' or 'systems' perspective on supply chain design, it is necessary to bring the actor (the decision-maker) into the centre of supply chain design research (Schorsch, Wallenburg, & Wieland, 2017), with its implications for theory and research design.

2.3.1. SUPPLY CHAIN COMPLEXITY AND DECISION-MAKING COMPLEXITY

The grounded work by Manuj and Sahin (2011) appears promising in offering a framework for integrating the actor into research on supply chain design. Manuj and Sahin (2011) link supply chain complexity to the complexity faced by the decision-maker (*supply chain decision-making complexity*), which is linked to realised supply chain performance. They define supply chain complexity as "*the structure, type and volume of interdependent activities, transactions, and processes in the supply chain that also includes constraints and uncertainties under which these activities, transactions and processes take place*" (Manuj & Sahin, 2011, p. 523). Supply chain complexity is thus similar to the objective complexity (Campbell, 1988) of the decision-making situation. Supply chain decision-making complexity is defined as "*the difficulty faced by a decision-maker…* [and] *it is a measure of the collective effort required for problem definition, data collection, problem analysis, solution implementation, and control*" (Manuj & Sahin, 2011, p. 523). Supply chain decision-making complexity is thus similar to perceived complexity (Campbell, 1988). It relates to an objective measure of complexity (*the level of supply chain complexity*), the individuals involved (*human cognitive moderators*) and the organisational structure around the decision-making (*strategic moderators*) as illustrated in Figure 2.2.

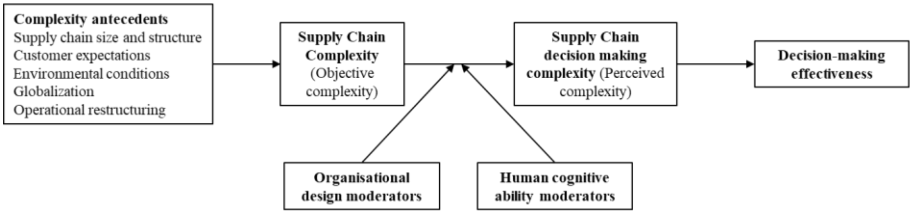

Figure 2.2: Supply chain complexity and supply chain decision-making complexity linked to decision-making effectiveness. Adapted from Manuj and Sahin 2011.

Although Manuj and Sahin (2011) address supply chain decision-making in general, and not explicitly supply chain design decisions, their framework is useful for exploring and investigating supply chain design decision-making and linking this to the analytical foundation. One important organisational design moderator is thus the analytical foundation underpinning decision-making. Manuj and Sahin (2011) refer to this as information system strategy and knowledge management. The framework thereby helps bridge the analytical perspective on supply chain design, with the role of complexity in decision-making. For this, it is necessary to consider an overarching theoretical frame for how decisions are made, and how and what role any analytical foundation plays in such a frame. This requires a suitable theoretical frame, recognising the behavioural aspect of decision-making and the cognitive limitations of boundedly rational decision-makers.

Such socio-behavioural perspectives are introduced by two theoretical lenses, the BTF (Cyert & March, 1963) and the IPV (Galbraith, 1974). The first, addressing how decisions are made, is thereby relevant for understanding how decision-makers arrive at a specific decision (Ketokivi, Turkulainen, Seppal, Rouvinen, & Ali-Yrkko, 2017). The second theoretical lens is concerned with the match between information processing need and capability, derived from task complexity and organisational design (Galbraith, 1974). In this way, it offers a perspective on the organisational frame surrounding the decision-maker and the supply chain design task. Both perspectives are complementary to an empirically grounded approach to improve the understanding of supply chain design decision-making, and thereby also improving practice. In the next sections, these two theoretical lenses and their relevance for addressing the applied research project are introduced.

2.3.2. BEHAVIOURAL THEORY OF THE FIRM

BTF, introduced by Cyert and March (1963), was presented as an alternative view of firm decision-making offering a socially enabled and constrained decision process. The BTF looks within the firm to understand how firms make decisions regarding price, output, resource allocation and innovation, among others (Mahoney, 2005). BTF offers a frame for understanding how such decisions are made based on four relational concepts: (1) Quasi-resolution of conflict, (2) uncertainty avoidance, (3) problemistic search, and (4) organisational learning. This theoretical frame is appealing to understand how supply chain design decisions are made, as it links findings and propositions from existing research on supply chain design decisions, as depicted in Table 2.2.

Table 2.2: Behavioural theory of the firm linked to supply chain design decision-making.

Relational concept	**In the behavioural theory of the firm** (Cyert & March, 1963)**:**	**Link to supply chain design decision-making**
Quasi-resolution of conflict	• Goals as independent constraints • Local rationality. • Acceptable-level decision rules • Sequential attention to goals	Numerous functions impacted by supply chain design decisions (Yang, Farooq, & Johansen, 2011) imposing conflicting or coherent goals. Departmental thought-worlds are influencing local rationality (Niranjan, Rao, Sengupta, & Wagner, 2014). Hierarchical and functional separation of supply chain design decisions (Meixell & Gargeya, 2005).
Uncertainty avoidance	• Feedback-react decision procedures • Negotiated environment	Increasing volatility of the global business environment to be considered during supply chain design decision-making (Christopher & Holweg, 2011). Policies and supply chain design strategies for supply chain resilience (Pettit, Fiksel, & Croxton, 2010; Wieland & Wallenburg, 2012)
Problemistic search	• Motivated search • Simple-minded search • Bias in search	The difficulty of predicting performance impact when changing complex interdependent systems, such as supply chains (Larsen, Manning, & Pedersen, 2013; Manuj & Sahin, 2011). Supply chain complexity is limiting the ability to identify optimal supply chain designs (Krægpøth, Stentoft, & Jensen, 2017). The influence of monetary quantification (Wouters, Anderson, Narus, & Wynstra, 2009) and management attention in complex cross-functional decision-making (Moschuris, 2008).
Organisational learning	• Adaption of goals • Adaption in attention rules • Adaption in search rules	How does experience lead to an improvement in supply chain design 'capability?' (Mihalache & Mihalache, 2016)

The BTF's suggestions of how bounded rationality influences decision-making forms the view of the supply chain design decision-making process in the thesis. Central to this is how optimising is replaced by satisficing. The aspirational level of decision-makers, primarily building on past performance, is crucial in determining a satisfactory solution and thereby when information search is stopped. Furthermore, choice alternatives and their consequences are revealed sequentially through search processes. As search processes are 'demanding'; decision-makers economise their effort, whereby the aspirational level again becomes important for determining the effort put into the search. When supply chain complexity increases, so do the difficulty of predicting future outcomes. Such increasing difficulty would have implications on decision-making, as it might result in attributing more resources for search and analysis to satisfy the aspirational level of the information search or lowering the aspirational level accepting the uncertainty associated with missing information. Further, the difficulty might not even be recognised by decision-makers, introducing the risk of ineffective decision-making.

An important contribution of the BTF is its ability to link the different elements of decision-making within the firm, with the role that bounded rationality assumes based on search behaviour and aspirational levels. While BTF suggests that the 'boundary' of rationality can be extended through revising search and decision-making rules (Cyert & March, 1963), it does not explicitly link the decision process to key determinants of the information processing capacity of the organisation. In other words, in one organisational context, choice alternatives and information search for supply chain redesign might flow more easily to decision-makers and require less processing in comparison to a similar supply chain redesign activity in a different organisational context. The IPV addresses this perspective.

2.3.3. INFORMATION PROCESSING VIEW

At the essence of IPV is the achievement of a fit between the information processing needs and the information processing capacity of an organisation (Galbraith, 1974) to ensure performance benefits. If the information processing need exceeds the available capacity, task performance would be impaired; while if the information processing capacity exceeds the need, the excessive resource would be wasted. Viewing supply chain design as a task that requires a certain level of information processing, it becomes relevant to embrace the organisational structure surrounding the task (supply chain design decision-making) to ensure a match between information processing capacity and information processing need.

Indeed, as supply chain complexity, and thereby decision-making complexity increases, so does the information processing need. Similarly, Manuj and Sahin (2011) discuss the importance of the organisational structure (e.g. scope and boundary management) in determining both the information processing need and capacity. IPV suggests that environmental, organisational and task complexity determines the information processing needs through the amount of uncertainty introduced. To match the information processing need, organisational control and design mechanisms of varying cost are deployed. For low uncertainty situations, standard operating procedures can ensure an efficient process, while for higher uncertainty, companies often rely on the hierarchy to reach decisions (Egelhoff, 1991), i.e. escalating a decision until it reaches a level with authority and a sufficiently holistic understanding to decide. As the organisation faces an increasing number of exceptions, the reliance on the hierarchy becomes overburdened, and other strategies are sought. Alternatively, approaches include goals, slack resources, self-contained tasks, or lateral relations to increase the information processing capacity to match the information processing need (Galbraith, 1974).

The IPV thus offers an alternative perspective on addressing the effectiveness of supply chain design decision-making, as the result of a fit between the information processing needs for the decision-making process, and the information processing capacity of the organisation undertaking the decision. Understanding how the organisational design influences supply chain decision-making complexity, and thereby the information processing need for supply chain design decision-making, as well as the information processing capacity for supply chain design decision-making, will complement existing work by Manuj and Sahin (2011).

2.4. SUMMARY

This chapter began by introducing and defining *‘supply chain design decisions’*. Following this, literature informing supply chain design decisions was synthesised. The synthesised literature can be characterised by building on a rationalist approach, in which clear preference ordering and modelling of causal effects of different choice alternatives allow for identifying an *‘optimal’* supply chain design. However, such a perspective is at odds with how supply chain decisions are made in practice. Grounded research by Manuj and Sahin (2011) points to the necessity of considering the decision-making complexity as perceived by the individual decision-maker.

To reflect this and based on the empirical observations in the case company, two behavioural and cognitive-oriented theoretical lenses are introduced. The BTF, applicable for operationalising bounded rationality in firm decision-making, and the IPV, linking the information processing capacity to the organisational structure surrounding decision-makers. These two theoretical lenses offer an empirically grounded frame for understanding supply chain design decision-making, a necessary step to move beyond developing and validating increasingly sophisticated and complex mathematical formulations (Ferdows, Vereecke, & De Meyer, Delayering the global production network into congruent subnetworks, 2016) that are disconnected from the everyday life of decision-makers. These lenses reflect that to advance both academia and practice within supply chain design, it is essential to deploy a more holistic approach, embracing the ‘soft’ side of supply chain management (Rodney, 2014) on top of advancing the analytical foundation underpinning supply chain design decisions.

CHAPTER 3. RESEARCH DESIGN

Central for the thesis is the creation of theoretical knowledge advancing the understanding of supply chain design decision-making simultaneously with advancing industrial practice. This two-fold objective promotes a research design building on extensive industrial collaboration. The following chapter outlines the design of this research, thereby addressing critical questions on which and why different research approaches have been deployed to address the three research questions, how the research approaches were applied, and how the quality of the research has been ensured.

3.1. RESEARCH APPROACH

3.1.1. RESEARCH PARADIGM AND METHODOLOGICAL APPROACH

Arbner and Bjerke (2008) sought to obtain a fit between ‘ultimate presumptions’, the problem investigated, and the method used to investigate it. Within a social science context, three dominating paradigms exist positivism, neo-positivism, and constructivism. These three paradigms are distinct in their conception of the world and scientific ideals. In a positive view, the world can be observed in the form of an objective reality. Studying this objective reality requires controlling for circumstances to obtain ‘true’ knowledge. In a neo-positivistic paradigm, the same ideals are intended. However, it is recognised that this is unobtainable, whereby the neo-positivistic paradigm embraces that research takes place in its natural setting. In the constructivist paradigm, reality is conceived as being subjective, so to achieve insight and understanding, it is necessary to embrace the perceived reality of the individual in a hermeneutic perspective. Such as perspective is consistent with the point that operations and supply chain management is a form of management research that *“cannot be separated from the complex context in which it resides”* (Coughlan, Draaijer, Godsell, & Boer, 2016, p. 1681), and that it is necessary for researchers in supply chain management dealing with ‘soft’ issues to deviate from traditional positivistic approaches (Halldórsson & Aastrup, 2003).

The context of this study, supply chain design decision-making, in which actors act according to individual and shared beliefs, performance aspirations, management systems, experiences, and time pressure, points to a scientific paradigm building on relativistic reality. Research in this domain should embrace human values and emotions, instead of excluding them, as suggested by Dunn et al. (1994). However, there are also elements that do exist independently of individuals in the form of material facts, e.g., inventory levels, invoiced purchase prices or capacity utilisation, as a physical manifestation of supply chain design decisions. Such elements need to be considered, and suggesting a multi-paradigmatic approach (Halldórsson & Aastrup, 2003), not relying solely on a constructivist paradigm.

Arbnor and Bjerke (2008) link such an ultimate assumption, i.e., paradigms and epistemological positions, to three methodological approaches, an analytical approach, systems approach and actors approach, which is again linked to an operative paradigm for how the research is conducted. All three methodological approaches appear intuitively relevant to the domain of supply chain design. The analytical approach, comparable to addressing the supply chain design problem through stylised and analytical tractable problems (Bertrand & Fransoo, 2009), builds on clear causality. Here 'positivistic' answers can be derived, and objectively substantiated (Arbnor & Bjerke, 2008). For the systems approach, the research area is addressed as a whole, whereby knowledge is dependent on the system, or context, within which the knowledge exists. Such a systems approach is reflected by the thinking that no single approach to supply chain design is optimal in all situations, but contingent on the context factors, such as product and process (Ferdows, Vereecke, & De Meyer, Delayering the global production network into congruent subnetworks, 2016), and that supply chains constitute complex adaptive systems. Finally, the actors approach, working from a paradigm of subjectivity dependent on actors (Arbnor & Bjerke, 2008), reflecting the notation of perceived difficulty in supply chain decision-making (Manuj & Sahin, 2011), positioning the actor as central for the study area.

In this research setting, the actors' approach appears especially appealing in addressing the 'how' of decision-making, but it is also clear that the outcome of actors' actions are made within and manifested in complex systems, and such decisions and their effects could be analytically tractable. This suggests the suitability of the analytical and systems approach in complementing the actors' approach, building on action research, as suggested by Arbnor and Bjerke (2008). In the following sections, how the operational paradigm is derived based on this methodological stance is discussed.

3.1.2. ACTION RESEARCH PROJECT AND ROLE OF THE PHD

The frame for this PhD project did not allow for complete discretion by the researcher in designing the research, e.g., it was predetermined that the PhD project would be conducted in close collaboration with the case company. Furthermore, the close interaction and interest of the industrial partner introduced expectations regarding the industrial partner being able to improve practice within supply chain design based on the research project. These requirements carried two significant ramifications for the research design. First, it helped focus the research project on a substantial practical problem, an essential point for ensuring relevant operations and supply chain management research (Coughlan, Draaijer, Godsell, & Boer, 2016). Second, it influenced the methodological stance of the project, through implicitly expecting the researcher to contribute to improved practice through active participation and action, setting the scene for an overall action-oriented research project. As such, the premises of the research project build on active involvement and submersion of the researcher in both practice and research. In this setting, interaction (Svensson, Ellström, &

Brulin, 2007) and action (Coughlan & Coghlan, 2002), besides analysis and reflection, become critical points.

Although the overarching frame for the research project was predetermined in terms of the case company, research theme, and the expectation of tangible improvement of practice, the researcher maintained a high level of discretion regarding the position within the research domain, research opportunities to pursue and how to pursue them. This discretion allowed the researcher to address both a practical and theoretical relevant problem when doing the action research (Näslund, 2002). With the theme of the practical problem given, a critical first step was relating the practical theme to existing literature, to identify potential theoretical contributions complementary to the practical problem. Although the researcher maintained discretion on the design and the execution of the research, an initial kick-off meeting was held with the steering committee for the research project, to align and agree on the planned research activities, their relevance and contribution to the industrial problem, and the role within the case company. Steering committee meetings were continuously held throughout the three-year period. These meetings were used to report on progress and adjust the research activities if needed, as suggested by Coughlan and Coghlan (2002). This approach ensured the flexibility of the research project, allowing the project to adjust based on research findings and emergent opportunities. Furthermore, it offered a channel for discussion and reflection on research findings, thereby contributing to the quality of the research.

The role of the researcher in field research can be classified into four types, ranging from the complete participant, the participant-as-observer, the observer-as-participant, and complete observer (Burgess, 2002). Throughout the three-year period of the research project, the researcher shifted between two roles, that of participant-as-observer and observer-as-participant. One crucial ethical consideration of navigating these two roles and not the role of the complete participant is that it was made explicitly clear for members of the organisation that a key interest for the researcher was to do research, either through contributing to action, observing action or both. These two roles fit well with the actor approach (Arbnor & Bjerke, 2008), enabling close interaction between the researcher and the individuals of the organisation, and thereby contributing depth and rich insight that is relevant for addressing the “how” questions of the research.

The shift between the role of participant-as-observer and observer-as-participant reflects that although the overall research setting is action research, with the researcher being emerged in and taking an active role within the organisation, the role of the researcher has continuously shifted between that of active participation with responsibility for the outcome, and that of observation, allowing different types of inquiry. When reporting on underlying research activities underpinning the PhD project, the former is reported building on action research (Coughlan & Coghlan, Action research for operations management, 2002; Näslund, 2002), while the latter is building on case research (Yin, 2014; Voss, Tsikriktsis, & Frohlich, 2002). The individual research activities are reported in the seven papers underpinning the PhD thesis. Each paper carries its individual justification of research design and methodology further detailed in Section 3.1.4. The focus in this chapter is therefore on the overall research frame, on which these seven papers build, and how they collectively contribute to addressing the overarching research objective and answering the identified research questions.

3.1.3. CASE JUSTIFICATION

The close industrial collaboration with the case company addressed one key aspect of doing empirical-based research, the one of obtaining sufficient access (Croom, 2009), in a research context concerning sensitive decisions regarding future production footprint and market presence (Ferdows, 2016). However, it is clear that access to data is not sufficient to merit the usefulness of the industrial case. Yin (2014) highlights five rationales for single-case design: *critical, unusual, common, revelatory* and *longitudinal.* The three latter are significant in justifying the selection of the case company. The case company is *common* for the research questions addressed: an OEM of complex manufactured goods operating with a global manufacturing footprint and supply base. The supply chain structure and challenges are therefore similar to industries within capital goods, such as heavy machinery, industrial equipment, aerospace or automobile. Researching supply chain design decision-making in this specific organisation can yield insight into how such decision-making processes unfold, and the determinants of their efficiency and effectiveness. Additionally, as supply chain redesign changes are characterised by substantial time separation between cause (decision-making) and effect (performance impact), the *longitudinal* approach and access allow the unfolding of events and the appearance of causal effects in supply chain redesign. This is combined with *revelatory* access to project team meetings, steering committee meetings and interviews across managerial levels for sensitive decision-making, substantiating the appropriateness of the case company as a single case.

More importantly, the single case study approach is appropriate for the research question posed by allowing the researcher to be at eye-level with project teams and decision-makers in the empirically rich and messy real-life environment where supply chain design decisions unfold. In this way, driving research building on "*what the decision-makers actually think*" and "*how they arrived at the specific decision*" in determining the design of their supply chain (Ketokivi, Turkulainen, Seppal, Rouvinen, & Ali-Yrkko, 2017), is appropriate for the scientific paradigm underpinning this research.

3.1.4. RESEARCH ACTIVITIES AND EMPIRICAL FOUNDATION

Building on the single industrial case, several different research activities have been conducted relying on the case study approach (Voss, Tsikriktsis, & Frohlich, 2002) and the action research approach (Coughlan & Coghlan, 2002; Näslund, 2002). These activities have been documented in seven academic writings, each carrying a partial contribution to answering the three research questions and achieving the overarching research objective to *improve supply chain design decision-making within the OEM*. Table 3.1 links the seven papers to the method and data sources used, and their contribution to answering the identified research questions.

Table 3.1: Research questions linked to methods, data collection and papers.

Research Question	Method	Data-sources	Contribution to research question	Paper
RQ1: How are supply chain design decision-making processes linked to realised supply chain design changes?	Embedded case study	Observations, interviews	Identified decision-making bias is resulting in increasing supply chain complexity if relying on monetary quantification	1
	Embedded case study	Observations, interviews, archival records	Exploring the role of supply chain complexity and management attention on the ability to predict the performance of new supply chain designs.	2
RQ2: How can the analytical foundation for supply chain design decisions be improved?	Conceptual paper	Literature, case	Development of a conceptual model and process for analysis of alternative supply chain designs.	3
	Action Research	Observations, interviews, workshops, archival records	Development of a mathematical optimisation model integrating strategic and tactical decisions for improved supply chain design decision-making. Numerical experiment to test under what conditions significant interactions exist between strategic and tactical decision-making.	4

	Quasi-experiment	Observations, interviews, archival records	Quantification of the monetary value of strategic-tactical interactions in supply chain design decision-making. Test decision-makers' ability to intrinsically valuate volume flexibility in supply chain design decision-making.	5
	Multi-case and conceptual model	Interviews, Archival records	Development and test of Probable Maximum Loss model for quantifying supply chain vulnerability.	6
RQ3: How does organisational design influence the supply chain design task?	Embedded case study / Social network analysis	Observations, Interviews, Archival records	Exploring the impact of organisational design on the effectiveness of the supply chain redesign task.	7

Figure 3.1 illustrates how the different papers are linked to different data sources and units of analysis, along with research activities conducted throughout the three-year span of the PhD project.

Throughout the three-year project, more than forty supply chain redesign decisions were made, either within a single factory or across multiple factories in the OEMs manufacturing network. The manufacturing network of the OEM consists of three different production business units (PBUs): PBU A, B, and C. Each PBU consists of six to eight factories, which have engaged in different supply chain design projects. Figure 3.1 depicts the supply chain design projects and associated factories that have been the unit of analysis for one or more research papers. As an example, a total of 12 supply chain design decisions were related to Factory A.1, with 10 of them being the unit of analysis of one of the research papers.

Each supply chain design project is shown as a square, depicting the duration of the decision-making and implementation process of the supply chain design change. The naming and appearance of the square reflect the association to a research paper. Based on the characteristics of the individual supply chain design project, a supply chain design project could be an embedded case in several research papers. For example, the supply chain design project named 1.B and 2.C was case B in Paper 1 and case C in Paper 2.

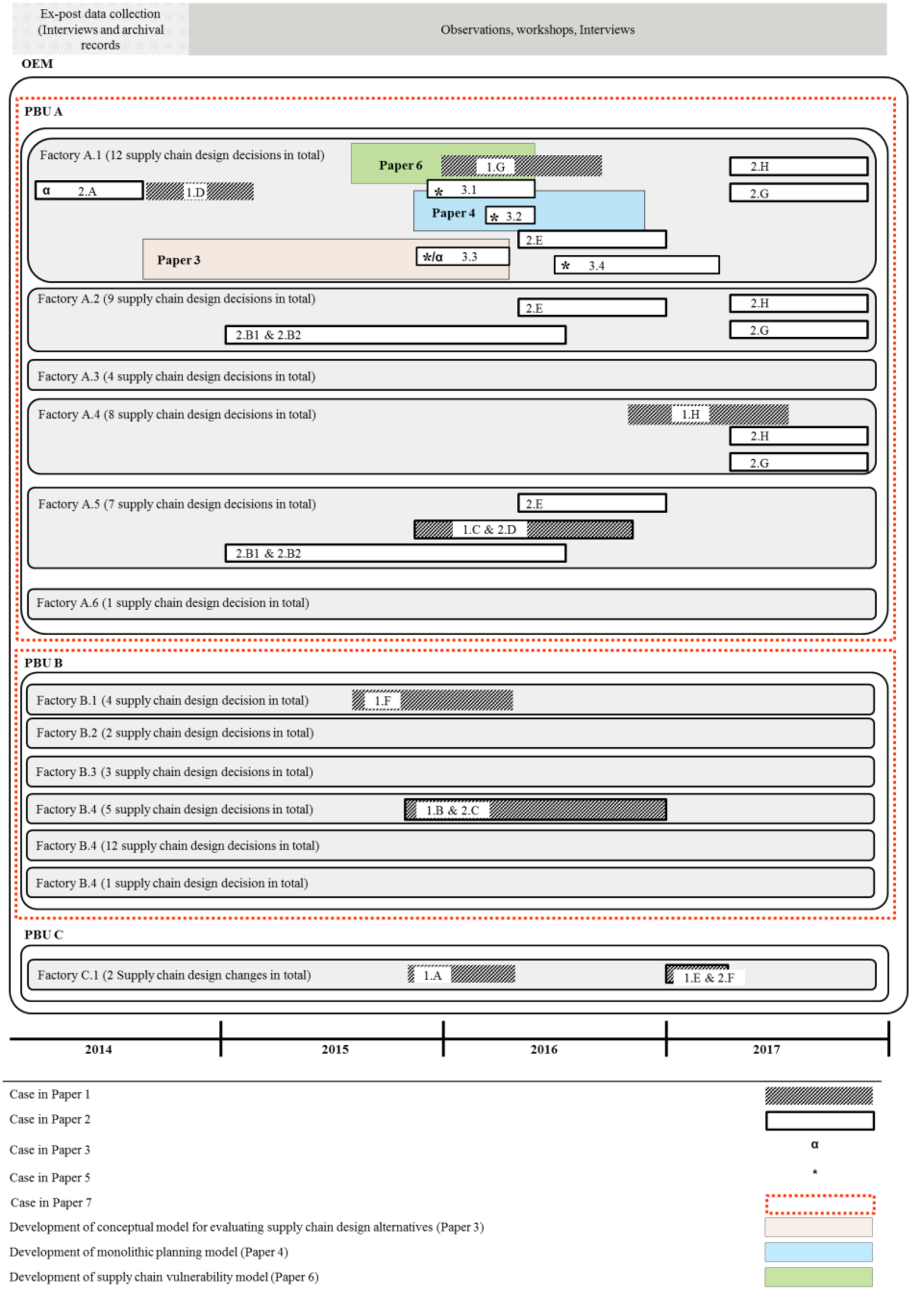

Figure 3.1: Overview of the unit of analysis and data collection methods for research activities

Addressing RQ1 builds on embedded case studies, with the individual supply chain design decision as the unit of analysis. Each supply chain design change has been investigated longitudinally from ideation and decision-making to implementation and realised outcome. In these investigations, several different data sources have been utilised to develop in-depth and detailed case narratives. The data sources ranged from observations of project team meetings and decision meetings, interviews with project participants and decision-makers, to the collection and analysis of archival records and transactional data from the OEM's ERP system. Based on this broad range of data, detailed and longitudinal case narratives for the supply chain design decision have been created.

Figure 3.2 illustrates one such case narrative for supply chain design decision 2.A, depicting the initial idea behind the supply chain design change, leading to a decision of whether to outsource the assembly process, and then the realised outcome.

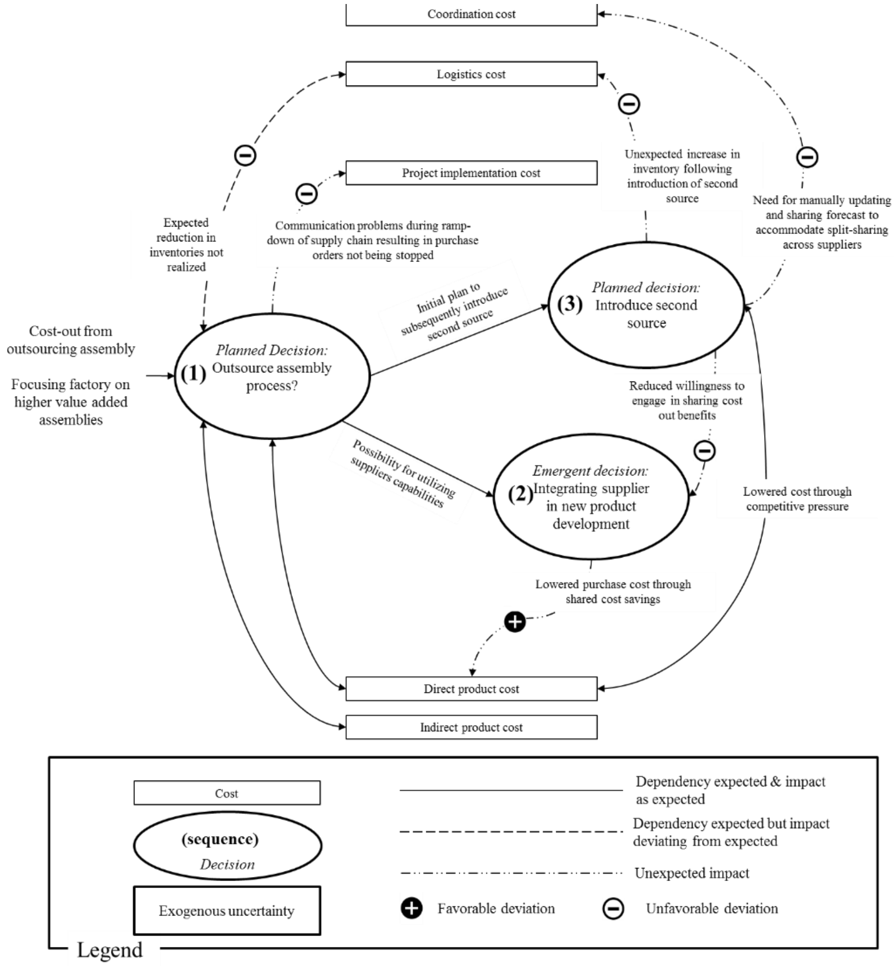

Figure 3.2: Illustrative case narrative for supply chain design based on decision 2.A.

These case narratives build on a rich empirical foundation, spanning decision-makers and project participants across the OEM. Substantiating the deep empirical richness of the case narratives supporting the thesis, Table 3.2 depicts how the researcher engaged with 283 people across functional and hierarchical levels.

Table 3.2: Involvement and interaction with stakeholders across functional and hierarchical levels.

Function/Hierarchical level	SVP	VP	D	M	S/PM/TL	Total
R&D and new product development	2	2	7	10	36	57
New Product Introduction		1	3		3	7
Purchasing	1	7	15	19	55	97
Manufacturing	3	12	5	16	35	71
Quality		1	2		3	6
Sales and supply chain planning	1	3	1	2	7	14
Service			3	5	3	11
Finance		1	3	1	15	20
Total	**7**	**27**	**39**	**53**	**157**	**283**

Note: *SVP: Senior-vice president, VP: Vice president, D: Director, M: Manager, S/PM/TL: Specialists, Project Managers, Team-leaders and other functional roles.*

Addressing RQ2 builds on a combination of different methodological groundings to improve the analytical foundation for decision-making based on the findings from RQ1. An action research approach was applied for developing and testing conceptual and mathematical models for improving supply chain design decision-making. A conceptual model seeks to address the biases and issues identified in RQ1 for evaluating alternative supply chain design decisions. Two mathematical models complement the conceptual model. A monolithic planning model for integrating strategic and tactical decisions and a model for quantifying supply chain vulnerability. To ensure sufficient depth and detail, the focus has been on conducting model development and testing in the context of a single factory. However, by mapping contextual variables and relating model parameters and development to existing literature, attention has been on ensuring that the proposed models and findings are generally applicable. Besides mathematical programming, addressing RQ2 further relies on quasi-experiments to offers insight into the quantification and the ability of managers to quantify elusive strategic-tactical dynamics resulting from supply chain design decisions.

Finally, for addressing RQ3, the unit of analysis shifted from the individual supply chain design decision and factory to the level of the PBU to investigate how organisational design influences the supply chain design task. This built on an embedded multi-case study of PBU A and B, investigating how the pattern of supply chain redesign is different among the two PBUs. Figure 3.1 thereby also reflects the progression through the study and shift in research methodology based on the emergent findings and research opportunities (Coughlan & Coghlan, 2002).

While each paper underpinning the PhD thesis builds on its individual research design, some general comments will be made in the next section on how the research quality has been ensured.

3.2. RESEARCH QUALITY

A fundamental question to be addressed when undertaking research is *"How can an inquirer persuade his or her audience that the findings of an inquiry are worth paying attention to?"* (Lincoln & Guba, 1985, p. 290). Validity and reliability are traditional criteria for judging research within supply chain management (Ellram, 1996; Mentzer & Flint, 1997; Mentzer & Kahn, 1995). However, such criteria are associated with a positivistic research paradigm, which is not suitable for the qualitative research paradigm employed in this research (Halldórsson & Aastrup, 2003). Instead, the four criteria of credibility, transferability, dependability, and confirmability will be driving the overall discussion on research quality.

3.2.1. CREDIBILITY

Departing from a paradigm that *'reality is constructed by and exists only in the minds of the respondents and their particular context. It is the degree of match between the respondent's constructions and researchers' representation of these that determines credibility'* (Halldórsson & Aastrup, 2003, p. 327), several steps were made to ensure the credibility of the research project. Formal and informal dialogue played a critical role in ensuring a match between the researcher's construction of reality and the actors' view. Steering meetings for the research project were used for a formal dialogue in which findings and reflections were presented and discussed with members from senior management and the thesis supervisor. Such meetings were conducted continuously, typically 2-3 times a year, throughout the project's duration. In addition to these steering meetings for the research project, five in-house seminars ranging from 1-5 hours were conducted with senior executives, middle management and functional specialists to engage in dialogue and reflection regarding research findings and progress. This formalised dialogue was an important step in ensuring the credibility of the constructed worldview. Furthermore, ongoing and informal dialogue enabled by being physically present in the case company offered another effective means for continuously discussing and reflecting on research findings, and ensuring the match and calibration between my constructed worldview as a researcher and that of the members of the organisation.

The extensive functional and hierarchical involvement across the case company further substantiates the credibility of the research conducted. The engagement with 283 different stakeholders, ranging from senior vice presidents to shop-floor workers, contributes to significantly reducing any bias from individual perceptions and functional worldviews persistent to supply chain management (Niranjan, Rao, Sengupta, & Wagner, 2014).

Finally, the fact that the research have lead to change within the organisation acts as an additional justification that a credible match between members of the organisation and the researcher was ensured. If such a match did not exist, it is unlikely to think that the researcher would have been able to convince and enact change within the organisation. Furthermore, academic peers have acted as an anchor point for critical reflection and thinking regarding observations, actions and outcomes. The engagement with five co-authors not personally nested within the case company helped to ensure an unbiased theoretical reflection.

3.2.2. TRANSFERABILITY

Different from a traditional perspective on external validity, concerned with establishing generalisation across identified populations, transferability is derived from the richness of the contextual understanding, through *"attempts to describe in great detail the interrelationships and intricacies of the context being studied"* (Halldórsson & Aastrup, 2003, p. 328).

Several efforts have been made to strengthen the transferability of the research, and thereby the trustworthiness of the results across time and space. First is the rich description of the context of the case company, and the research setting, leading to the initiation of the research project. Additionally, there is an in-depth description of interrelationships and logical reasoning when reporting the research activities, e.g., exemplified by the case narrative, thereby allowing the reader to understand the context and situation leading to the proposed relations and findings.

3.2.3. DEPENDABILITY

Reliability, as a precondition to validity in a positivistic approach, is concerned with the robustness of measurement results, i.e., measurement tools providing consistent results when subjected to the same preconditions. In an action research approach, characterised by the involvement of actors and the emergent nature of the situation, such goals are not attainable. Rather, shifts in research design and constructs are indicators of successful research (Erlandson, 1993). In such a context, dependability is based on documenting, explaining and making transparent the logic behind the research design and any shifts (Lincoln & Guba, 1985). Each individual research paper justifies the choice of research design on its own, e.g., in Paper 2, the research design was focused on identifying supply chain design decisions driven by total cost reductions to justify cost estimation accuracy as an indicator of decision-making effectiveness. Similarly, shifts between methodology, e.g., from case-study to mathematical modelling, as a response to research findings, is depicted and explained in this chapter and further substantiated in subsequent chapters.

3.2.4. CONFIRMABILITY

Positivistic discussions of research quality address the aspect of *objectivity*. However, as is clear from the research paradigm underpinning this PhD thesis, the reality is partly an individual construction, thus making it impossible to obtain a single observable objective truth. Instead, to ensure research quality, focus should be placed on confirmability, through enabling the tracing of research findings to their underpinning sources (Halldórsson & Aastrup, 2003; Erlandson, 1993). The presentation of detailed data supports this, and how this data links to propositions and suggestions. Furthermore, through the submission of the individual research activities for peer-review in international journals and presentations at international conferences, the proposed connection between data and research findings has been subjected to rigorous external review.

CHAPTER 4. SUPPLY CHAIN DESIGN: DECISION-MAKING PROCESS

To advance the understanding of how decision-making practice influences supply chain design, this chapter seeks to address RQ1: "*How are supply chain design decision-making processes linked to realised supply chain design changes?*"

The research question was addressed by taking an empirically grounded view on supply chain design decision-making, getting at eye level with decision-makers during ideation, decision-making and subsequent implementation of supply chain design changes. Figure 4.1 contrasts the pattern observed in the OEM with existing literature on supply chain design (Chopra & Meindl, 2004; Meixell & Gargeya, 2005; Kirkwood, Slaven, & Maltz, 2005). The detailed study of supply chain design decision-making showed a path for supply chain design where *'overall configuration'*, understood as the centralised and coordinated identification of an optimal supply chain design (Meixell & Gargeya, 2005), is of less importance. Instead, the pattern observed within the OEM reflects how strategic guidance and unsatisfied performance aspirations lead to the initiation and scoping of supply chain redesign projects. The individual supply chain design changes are then evaluated financially on a case-by-case basis against the existing supply chain design. Supported by the financial evaluation, decisions are made for the individual supply chain design change. If it is decided to implement changes, they are either applied directly in the supply chain or through product design changes. This pattern is consistent with the predictions from BTF: Information search is problemistic, and decision-makers are satisficing, rather than optimising. Changes to the supply chain design are initiated because an aspirational level is not being satisfied. The specific change is then evaluated in isolation against prior performance to assess if the desired aspirational level can be satisfied by changing the supply chain design.

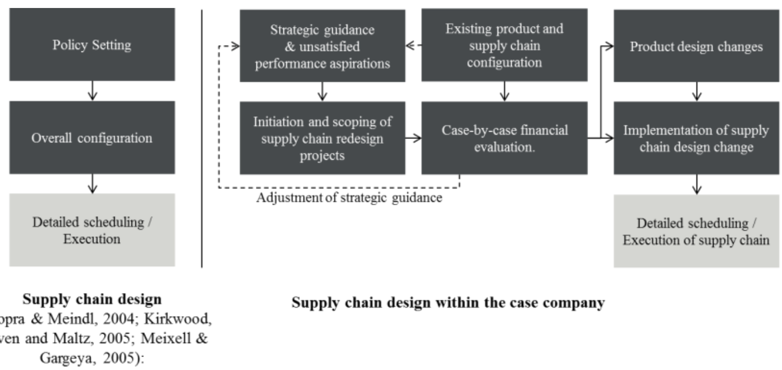

Figure 4.1: Pattern of supply chain redesign within the OEM compared to literature.

Following the emergent nature of the research within the case company, it was evident that supply chain complexity had a central influence on supply chain design decision-making, together with the importance of financial evaluations. This was exemplified in the OEM by the deliberate focus on reducing supply chain complexity through supply chain redesign and by the difficulty of deciding upon and implementing supply chain design changes. This is consistent with contemporary research, identifying complexity as an important barrier for supply chain redesign (Krægpøth, Stentoft, & Jensen, 2017), although it remains poorly understood how complexity influences behavioural aspects and decision-making in a supply chain context (Schorsch, Wallenburg, & Wieland, 2017). Improved understanding of the role of supply chain complexity in supply chain design decision-making was, therefore, an important element in advancing supply chain design decision-making (Schorsch, Wallenburg, & Wieland, 2017), as well as practice within the case company.

The deep engagement in the decision-making processes helped to unravel how information search and analysis is conducted, how the information is judged, and how supply chain complexity influenced the decision-making processes. The details of this work are reported in Paper 1 *(The Link Between Supply Chain Design Decision-Making and Supply Chain Complexity: An Embedded Case Study)* and Paper 2 *(Cost estimation accuracy in supply chain design: The role of decision-making complexity and management attention)*. In this chapter, the findings from Paper 1 & 2 are summarised, extended and discussed to answer RQ1.

The chapter is structured into three sections. The first section elaborates on the link between supply chain design decision-making and supply chain complexity. This is done by first extending the operationalisation of supply chain complexity and supply chain change complexity introduced in Paper 1. Next, findings from the case analysis are summarised, and the importance of monetary quantification is discussed. The second section picks up on the importance of monetary quantification by discussing and extending the analysis in Paper 2 regarding the role of supply chain complexity and management attention on cost estimation ability. Finally, the findings are summarised and synthesised.

4.1. THE LINK BETWEEN SUPPLY CHAIN DESIGN DECISION-MAKING AND SUPPLY CHAIN COMPLEXITY

Paper 1 improves the understanding of the link between supply chain design decision-making and supply chain complexity, thus creating more clarity on how supply chain complexity influences supply chain design decision-making and vice versa. This was achieved by investigating (1) the complexity of the supply chain being changed, (2) the complexity of the change to the supply chain, (3) the driver behind the suggested change, (4) the decision process, and (5) the realised outcome.

4.1.1. OPERATIONALISATION OF SUPPLY CHAIN COMPLEXITY AND CHANGE COMPLEXITY

Based on extant literature and interviews within the case company, a multidimensional scoring of supply chain complexity and supply chain change complexity was proposed in Paper 1. The operationalisation of this multidimensional scoring is further detailed in the following. Table 4.1 lists each variable for supply chain complexity, their link to existing literature, and the scale for operationalising. Details that were left out of Paper 1 for the sake of brevity. Dependent on the nature of the underlying supply chain characteristic, the variable is either operationalised through ordinal scales (OS) or relative scoring (RS). Characteristics, with qualitative differences, e.g., the type of manufacturing process, are operationalised through ordinal scales. Characteristics with quantitative differences, e.g., the number of suppliers, are operationalised by relative scoring with the minimum value equalling 1 and the maximum value equalling 5.

Similarly, Table 4.2 introduces the variables underlying the supply chain change complexity. Ordinal scales ranging from 1 to 4 were used for supply chain change complexity. For each supply chain redesign case, the supply chain complexity and supply chain change complexity was calculated as the mean across all variables.

Table 4.1: Mapping of supply chain complexity.

			Supply Chain Complexity Low (1) → High (5)			**Source**	**Scal e**
Supply Chain Characteristics	**Internal manufacturing and network**	Depth and width of Bill-of-Materials (BOM) *(Number of parts)*	Few (1) →Many (5)			(Bozarth, Warsing, Flynn, & Flynn, 2009; Manuj & Sahin, 2011)	RS
		Type of manufacturing process	Repetitive flow (1)	Batch production (3)	Customised (5)	(Bozarth, Warsing, Flynn, & Flynn, 2009)	OS
		Internal capacity constraints (bottleneck equipment) *(Number of bottleneck resources in each plant)*	Few (1) →Many (5)			(Jacobs, Berry, Whybark, & Vollmann, 2011; Goldratt & Cox, 1984)	RS
		Product and process design maturity *(Time between changes)*	Long (1) → Short (5)			(Bozarth, Warsing, Flynn, & Flynn, 2009)	RS
		Stability of production schedule *(CoV of production plan)*	Stable (1) → Unstable (5)			(Manuj & Sahin, 2011; Bozarth, Warsing, Flynn, & Flynn, 2009)	RS
		Extent of global production (*Number of plants and their global dispersion)*	Single/few local plants (1)	Few regional plants (3)	Several global plants (5)	(Christopher & Holweg, 2011)	OS
	Downstream	Demand variability *(CoV of demand)*	Low (1) → Hugh (5)			(Bozarth, Warsing, Flynn, & Flynn, 2009; Gupta & Marens, 2003)	RS
		Number of sales channels and customers	Few (1) → Many (5)			(Manuj & Sahin, 2011; Bozarth, Warsing, Flynn, & Flynn, 2009)	RS
		Heterogeneity of sales channels and customer needs	Customer needs mostly similar across sales channels and customers (1)	Some difference between customer needs across sales channels and customers (3)	Low similarity between customer needs across sales channels and customers (5)	(Manuj & Sahin, 2011; Bozarth, Warsing, Flynn, & Flynn, 2009)	OS
		Product life cycles (Average lifetime of products/services)	Long (1) → Short (5)			(Manuj & Sahin, 2011; Bozarth, Warsing, Flynn, & Flynn, 2009)	RS
		Extent of global sales	Customers are mainly local (1)	Customers are mainly regional (3)	Customers are mainly global (5)	(Christopher & Holweg, 2011)	OS

<table>
<tr><td rowspan="7"></td><td rowspan="6">Upstream</td><td>Number of suppliers that needs to be managed</td><td colspan="15">Few (1) → Many (5)</td><td>(Manuj & Sahin, 2011; Bozarth, Warsing, Flynn, & Flynn, 2009)</td><td>RS</td></tr>
<tr><td>Delivery lead time and variability</td><td colspan="15">Short and stable (1) → Long and unstable (5)</td><td>(Bozarth, Warsing, Flynn, & Flynn, 2009)</td><td>OS</td></tr>
<tr><td>Governance mode</td><td colspan="3">Market (1)</td><td colspan="3">Modular (2)</td><td colspan="3">Relational (3)</td><td colspan="3">Lead-firm (4)</td><td colspan="3">Integrated (5)</td><td>(Gereffi, Humphrey, & Sturgeon, 2005)</td><td>OS</td></tr>
<tr><td>Upstream capacity constraints (bottleneck items)</td><td colspan="15">Few (1) → Many (5)</td><td>(Jacobs, Berry, Whybark, & Vollmann, 2011; Manuj & Sahin, 2011)</td><td>RS</td></tr>
<tr><td>Raw material price uncertainty and importance for competitiveness</td><td colspan="5">Stable raw material prices / raw material prices of limited importance for competitiveness (1)</td><td colspan="5">Some instability in raw material prices with importance for competitiveness (3)</td><td colspan="5">Unstable raw material prices with significant importance for competitiveness (5)</td><td>(Gupta & Marens, 2003) (Christopher & Holweg, 2011)</td><td>OS</td></tr>
<tr><td>Extent of global sourcing</td><td colspan="5">Mainly local (1)</td><td colspan="5">Mainly regional (3)</td><td colspan="5">Mainly global (5)</td><td>(Christopher & Holweg, 2011; Manuj & Sahin, 2011)</td><td>OS</td></tr>
<tr><td colspan="2">Interdependence in supply chain flow</td><td colspan="5">Pooled (1)</td><td colspan="5">Sequential (3)</td><td colspan="5">Reciprocal (5)</td><td>(Van de Ven, Delbecq, & Koening, 1976)</td><td>OS</td></tr>
</table>

OS: Ordinal scale from 1-5
RS: Relative scale with minimum value = 1 and maximum value = 5.

Table 4.2: Mapping of supply chain change complexity

		Supply chain change complexity Low (1) → High (4)				**Source**
Area of change	Source (upstream changes)	No change (1)	New supplier, same geographical location (2)	New supplier, new geographical location (3)	Change ownership of activity (4)	(Manuj & Sahin, 2011)
Area of change	Make (Changes to internal manufacturing network)	No change (1)	Shifting production to a known location of proximity (onshore insourcing) (2)	Outsourcing production to a known location of close proximity (onshore outsourcing) or internally owned production in an offshore location (captive offshoring) (3)	Outsource production to an unknown offshore location (offshore outsourcing) (4)	(Larsen, Manning, & Pedersen, 2013; Fredriksson, Wänström, & Medbo, 2014)
Area of change	Deliver (downstream changes)	No change (1)	New distribution setup, same geographical location (2)	New distribution, new geographical location (3)	Change ownership (4)	(Milgate, 2001)

The operationalisation of supply chain complexity and supply chain change complexity was used as the framework for investigating how complexity influence supply chain design decision-making.

4.1.2. CASE FINDINGS: THE IMPORTANCE OF MONETARY QUANTIFICATION

Applying the suggested framework for within and cross-case analysis of seven supply chain redesign projects enabled an understanding of how supply chain complexity influences decision-making and realised outcomes. Figure 4.2 summarises the mapping of the seven embedded cases in the two dimensions of supply chain complexity and change complexity. For supply chain complexity, both the ex-ante and ex-post complexity is depicted,[2] thus reflecting the transition undertaken by changing the supply chain design.

[2] For decisions where it was decided not to implement changes, the intended change to supply chain complexity was mapped based on predicted changes to each dimension in Table 4.1.

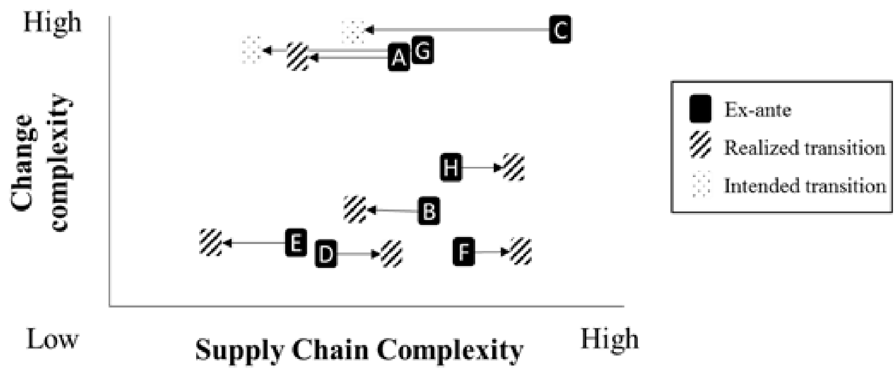

Figure 4.2: Supply chain complexity and change complexity (Asmussen, Kristensen, & Wæhrens, 2017)

Combining the mapping depicted in Figure 4.2 with the driver behind the supply chain redesign and investigating the unfolding of the decision-making process allowed for several findings to be distilled (Asmussen, Kristensen, & Wæhrens, 2017):

- The level of supply chain change complexity determines the potential for supply chain complexity reduction. However, the higher the supply chain change complexity, the higher the need for functionally specialised resources for the detailed design of the new supply chain and the produced product, e.g., the design of transport equipment, changes in material specification or changes to product design, to arrive at a decision point.
- The higher the supply chain complexity, the higher the need for analytical resources for analysing the consequences of proposed supply chain design changes.
- Supply chain complexity and change complexity in combination increased the difficulty decision-making *(supply chain decision-making complexity),* as the number of design alternatives to be evaluated and difficulty of establishing causal links increased, thereby requiring more time and effort for reaching a decision point.
- A systematic bias resulting from the low transparency on the marginal impact of supply chain complexity and changing supply chain system behaviour (e.g. increased inventory levels).

The last point is essential, considering the importance of the case-by-case financial evaluation of supply chain design changes within the OEM. When each decision is analysed in isolation, the low visibility of the consequences of increasing or decreasing supply chain complexity results in biased decision-making. Existing literature argues that monetary quantification, and the expectation of justification towards management, leads to improved decision-making by reducing perceived uncertainty (Wouters, Anderson, Narus, & Wynstra, 2009). Although monetary quantifications *"suggest a more thorough and careful analysis (Kadous et al., 2005), which project leaders are expected to show when senior management requires decision justification."* (Wouters, Anderson, Narus, & Wynstra, 2009, p. 67), the findings from the OEM show that a high reliance on monetary quantifications increases the risk of biased decision-making, particularly if the expectation of monetary quantification is not matched by an ability to make such quantifications. The limited ability to quantify all benefits in monetary terms impaired the pursuit of initiatives that were identified as being of strategic interest (e.g., initiatives targeted at increasing volume flexibility or reducing supply chain complexity), as non-monetary benefits were given less significance in decision-making. Although with substantial managerial attention, it was possible to ensure the attribution of value to strategic benefits that were not quantified in monetary terms. However, influencing decision-making in this way required the use of scarce management time. In the absence of management attention, supply chain design decisions remained based primarily on standard cost accounting principles, with an emphasis on directly quantifiable and traceable direct product cost (i.e., purchase price or direct labour cost). Consequently, the realisation of non-monetary performance benefits, e.g., flexibility, was contingent on complementary monetary benefits.

Faced by a need for decision justification, the capability to quantify and predict future outcomes, becomes an essential element of the supply chain design capability, together with the effective allocation of management attention. The next section, building on Paper 2, further explores the ability to predict future performance as part of supply chain design decision-making, while Chapter 5 addresses the development of the analytical foundation underpinning supply chain design decision-making.

4.2. THE ABILITY TO PREDICT PERFORMANCE OF SUPPLY CHAIN DESIGN CHANGES

Having established the importance of predicting future performance, especially in financial terms, Paper 2 dives deep into the ability of decision-makers to predict future cost when evaluating supply chain design changes accurately. This is done by exploring the relationship between supply chain decision-making complexity, management attention and cost estimation accuracy across ten cost driven supply chain design decisions.

While detailed within and cross-case analysis of the longitudinal study of the ten supply chain design decisions is presented in Paper 2, the following sections complement the findings presented in the paper by elaborating on the relationship between supply chain decision-making complexity, management attention and cost estimation accuracy

4.2.1. THE ROLE OF SUPPLY CHAIN DECISION-MAKING COMPLEXITY AND MANAGEMENT ATTENTION

Across the 10 cases, 51% of the variance in the cost estimation accuracy was explained by supply chain decision-making complexity (R^2 of 0.51 for the linear relationship between the ordinal rankings of supply chain decision-making complexity and cost estimation error), as illustrated in Figure 4.3. While the sample size is limited, the detailed case evidence supports the claim that supply chain decision-making complexity is significant in explaining cost estimation accuracy.

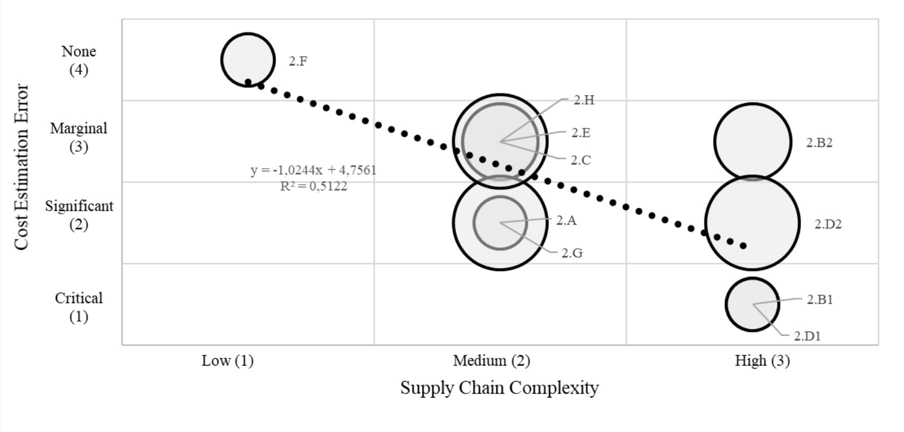

Figure 4.3: Relationship between supply chain complexity and cost estimation accuracy (Size of circles indicate management attention).

Beyond showing the detrimental effect of complexity on the ability to predict the future performance of supply chain design changes, a contribution is made by showing how the two types of supply chain complexity, detail and dynamic (Bozarth, Warsing, Flynn, & Flynn, 2009), influence the strategies for information search and analysis. For detail complexity, where complexity was visible, due to the numerousness of, e.g., item numbers or suppliers, decision-makers recognised the need for deliberate strategies for addressing the complexity at hand. This sets an aspirational level (Cyert & March, 1963) for the validity of the predicted performance, besides the predicted performance itself. This induced certain behaviours, such as detailed validation of input data, which reduced cost estimation errors due to, e.g., errors in input data. When the complexity was less evident, there were not the same deliberate choices of strategy nor behaviour induced, as the aspirational level remained focused on the predicted performance, and not the validity of the predictions. This resulted in significant cost estimation errors, which could be traced to errors in the collected input and master data. Such findings correspond well with research pointing to unreliable master data as a substantial barrier for supply chain redesign (Krægpøth, Stentoft, & Jensen, 2017). However, the findings presented here offer a more nuanced perspective, showing that supply chain complexity has a double-edged impact on the cost estimation ability. If it is visible that decision-making complexity is high, it can be recognised in the decision-making process and information search strategies, reducing the risk of cost estimation errors imposed. Oppositely, when the difficulty of the decision-making situation is not recognised, these behaviours are not induced, resulting in a high residual risk of cost estimation errors. However, even when the difficulty of the situation is recognised, it might not be sufficient to overcome the difficulty of the causal ambiguity and uncertainty in complex decision-making. Substantiating that a negative relationship exists between supply chain decision-making complexity and cost estimation accuracy as depicted in Figure 4.4.

From the supply chain redesign activities within the OEM, it was evident that there were substantial differences in the amount of managerial attention given to the individual supply chain design decision. This could be expected due to differences in managerial perceptions of importance. However, it raises the question of how such management attention influences the decision-making process and thereby cost estimation accuracy. Figure 4.4 depicts this relationship between cost estimation accuracy and management attention. The single case of low supply chain complexity is excluded (Case 2.F), due to the expectation that for a simple decision, the decision would not be improved by adding the oversight and insight of senior management. Excluding the low complexity case, management attention would explain 27% of the variance on cost estimation accuracy (R^2 of 0.27 for the linear relationship between the ordinal rankings of management attention and cost estimation error). Again, although the sample size is limited, the detailed case evidence and study of the actors' behaviours underpin that managerial attention is essential for cost estimation accuracy.

The cross-functional nature of supply chain design changes (Moses & Åhlström, 2009; Yang, Farooq, & Johansen, 2011) and their potentially conflicting objectives would suggest that management attention could be prone to conflict or unaligned goals (Marshall, Ambrose, McIvor, & Lamming, 2015), leading to either a dialectic process improving decision-making through sound questions, or political behaviour that is dysfunctional for decision-making effectiveness. Classifying management attention as being based on either coherent or conflicting goals showed that the nature of management attention influenced the behaviour during decision-making. While the sample size is too limited to infer statistical validity, the behaviours observed substantiates that while management attention based on conflict reduces cost estimation errors, the effect is less significant from management attention based on coherent goals, due to the difference in behaviour induced by the two different types of management attention. The contribution from conflict-based management attention in improving the estimation ability rested on the introduction of an aspirational level for the validity of the predictions, the introduction of competing solutions, and by imposing a future-oriented aspirational level, rather than an aspirational level based on past performance. The introduction of competing solutions extended the scope comprehensiveness of each solution by ensuring comparable cost estimation scopes across the competing solutions. In this way, intended or unintended scope errors made by one of the project teams were eliminated. Furthermore, having future alternative options required decision-makers to change the aspirational level from improving past performance to identifying the best future alternative. This required the collection of future-oriented data, resulting in cost estimations becoming better aligned with the future realised performance.

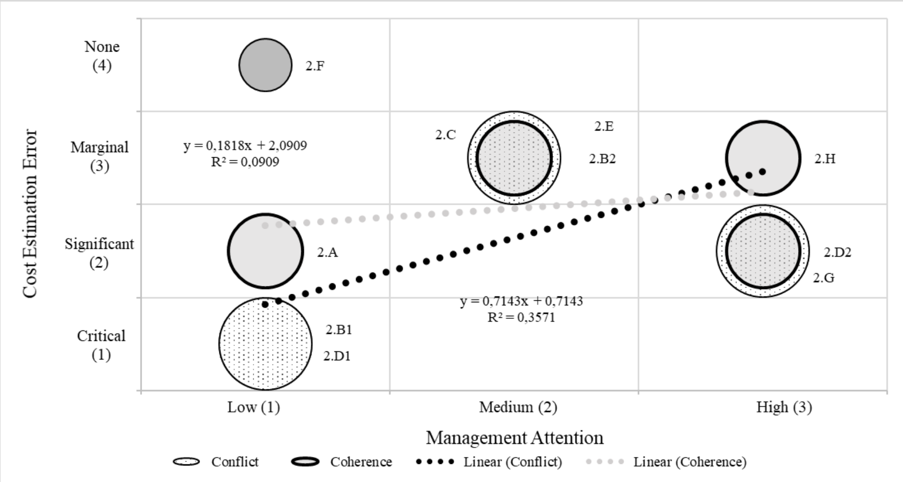

Figure 4.4: Relationship between management attention and cost estimation accuracy. (Size of circles indicate supply chain complexity)

When addressed in isolation, both supply chain decision-making complexity and management attention appear important for cost estimation accuracy. The case evidence further points to interaction effects between the two. Indeed, adding an interaction effect between complexity and management attention to the linear relationship between complexity and cost estimation accuracy increases the predictive power to explain 59% of the variance in cost estimation accuracy. However, the interaction effect is not significant. If only considering management attention based on conflict, the explanatory power increases to 67%, with both complexity and the interaction effect between management attention and complexity being significant at the 0.1 level.

4.2.2. ALLOCATION OF MANAGEMENT ATTENTION

The findings discussed above point to the importance of ensuring an appropriate level of management attention for supply chain design decision-making, a consideration that is not addressed in existing empirical research on supply chain design decision-making (Larsen, Manning, & Pedersen, 2013; Johansson & Olhager, 2018; Krægpøth, Stentoft, & Jensen, 2017). Substantiating the importance of ensuring an appropriate level of management attention is that there is no evidence of management attention being allocated based on decision-making importance (i.e., annual cost impacted) or decision-making difficulty (i.e., supply chain decision-making complexity). As illustrated in Figure 4.5, for both annual cost impact and supply chain decision-making complexity, R^2 of the linear relationship to management attention is below 0.1. Signifying that neither impacted cost nor decision-making explain the level of management attention during decision-making. An important point for firms seeking to develop their supply chain design capability must, therefore, be the development of an appropriate governance structure, ensuring involvement of the right stakeholders at the appropriate managerial level (Moses & Åhlström, Nature of functional involvement in make or buy decision processes, 2009). This is especially true for firms pursuing supply chain redesign to realise cost efficiency, as management attention is significant in improving estimation ability, and thereby reduces the risk of erroneous decision-making.

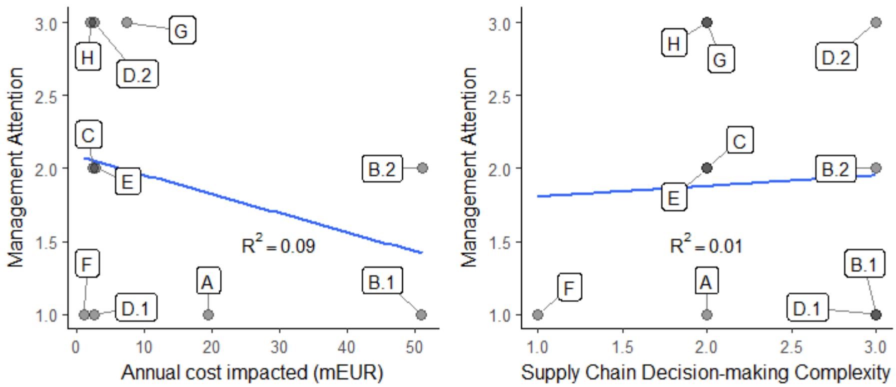

Figure 4.5: Relationship between management attention and decision-making importance (Annual cost impacted) and decision-making difficulty (supply chain decision-making complexity) for the ten supply chain design decisions.

4.3. SYNTHESIS

From the analysis of supply chain design decision-making, several theoretical and practical implications appear on the link between supply chain design decision-making and realised outcome. These are summarised into the following propositions:

> **P4.1:** The following supply chain characteristics increase supply chain decision-making complexity: the number of items, bottleneck items, the extent of global operations, the number of production facilities and the extension of lead times and planning horizons.
>
> **P4.2:** The extent of change to the supply chain design increases supply chain decision-making complexity through an increase in the solution space.

P4.3: The type and visibility of complexity influence decision-making processes through the enactment of different strategies for information search and analysis. A high level of detail complexity (e.g. numerousness of items or suppliers) leads to the enactment of strategies (e.g. sampling) that introduce an aspiration level for the accuracy of future performance predictions. A high level of dynamic complexity (e.g. reciprocal interdependencies) results in decomposition of supply chain design decisions, increasing risk of estimation errors.

P4.4: Management attention is positively linked to the aspirational level for supply chain design decision-making and the resources consumed in meeting this aspirational level.

P4.5: management attention is not initially allocated based on the difficulty (supply chain decision-making complexity) or the potential impact of a supply chain design decision.

P4.6: Supply chain design decision-making effectiveness is negatively affected by supply chain decision-making complexity and positively affected by management attention, at the cost of time and resources invested in decision-making.

These propositions reflect how the supply chain characteristics and change to the supply chain influence the difficulty of the decision-making (the link between supply chain complexity, change complexity and supply chain decision-making complexity), how decision-makers estimated future cost performance (information search and analysis in the decision-making process), and how the supply chain decision/making complexity and management attention influenced the ability to predict future performance and decide accordingly (supply chain design decision-making effectiveness) as depicted in Figure 4.6.

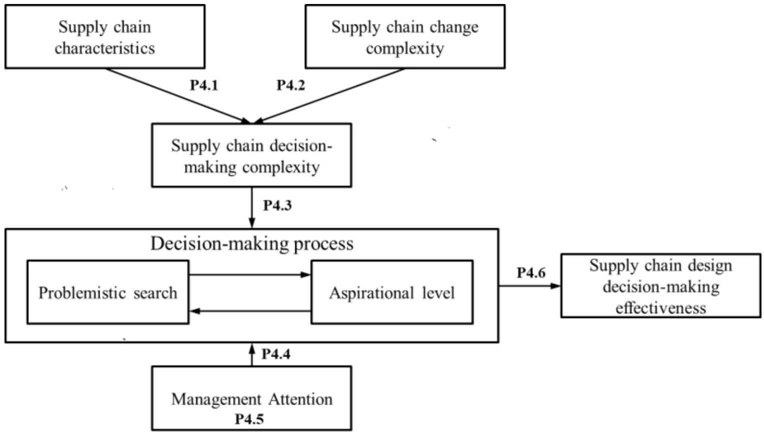

Figure 4.6: Proposed relationships between variables of supply chain design decision-making (Adopted from Paper 1 & Paper 2)

Consistent with elements from BTF, namely problemistic search and aspirational levels, it is proposed that supply chain decision-making complexity determines a trade-off between time and resources for information search and cost estimation accuracy, as depicted in Figure 4.7. Management attention is essential in determining the aspirational level for the analysis of supply chain design alternatives, and thereby also drives the allocation of time and resources for the analysis. An important element in improving the trade-off between time and resource and decision-making accuracy is the development of an analytical foundation supporting the search, filtering and analysis of relevant information (Manuj & Sahin, 2011) and thereby extending the boundary of the rationality of decision-makers (Kaufmann, Michel, & Carter, 2009). Such an analytical foundation would also contribute towards addressing the decision-making bias resulting from the low visibility on the marginal impact of reducing or increasing supply chain complexity or system behaviour. The following example illustrates this: if the decision-maker is in possession of a valid simulation model depicting the operational impact and consequences of choosing an offshore supplier over a local onshore supplier, the difficulty faced by the decision-maker would be lower, relative to the situation where the decision-maker intuitively knows there is an operational impact on inventory and service level but is unable to compare that impact too, e.g., the difference in purchase price.

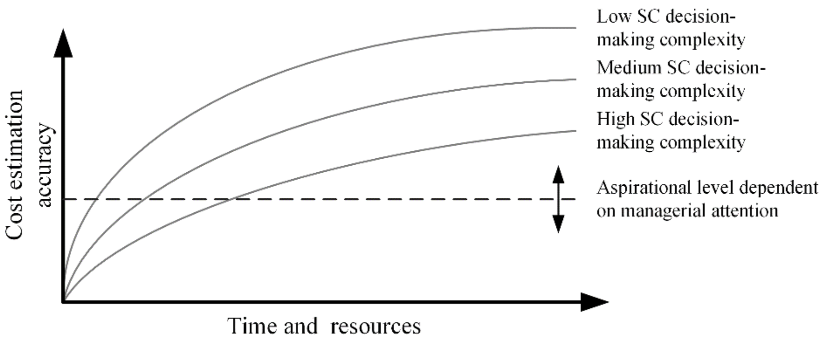

Figure 4.7: Supply chain decision-making complexity determining the trade-off between time and resource for information search and cost estimation accuracy

In advancing such an analytical foundation, the analysis of supply chain design decision-making within the OEM pointed to the following issues that need to be addressed:

1. Limited scope comprehensiveness in information search and analysis, leading to cost estimation errors. Reliance on the directly observable 'cost'. Standard cost accounting principles are poor at supporting partial and decentralised supply chain design decision-making. This leads to biased decision-making not penalising supply chain complexity.
2. No or limited consideration of the impact on system behaviour when evaluating supply chain design changes. Reflected by the insufficient consideration of potential upsides, e.g., increased volume flexibility when outsourcing production, or potential downsides, e.g., increase in inventory levels if changing to an offshore supplier with long transport lead-time and large order quantities. Leading to cost estimation errors and barriers to implementing strategic changes
3. Supply chain design decision-making entails a limited focus on supply chain vulnerability and resilience. If considered, it builds on simple policies, e.g., the use of dual sourcing within a commodity. However, such policy decisions are not revised when deciding on supply chain design changes, inducing a risk of changes in the supply chain vulnerability not being matched by appropriate changes in policies for supply chain resilience.

CHAPTER 5. SUPPLY CHAIN DESIGN: THE ANALYTICAL FOUNDATION FOR DECISION-MAKING

The purpose of this chapter is to outline the findings addressing RQ2: *"How can the analytical foundation for supply chain design decisions be improved?"*

This chapter builds on the realisation that coping with fast-paced environments and intensifying competition requires effective and efficient decision-making processes to ensure successful supply chain redesign. Effective is understood as making a *rational* choice by exploring relevant alternatives and predicting their future outcomes, and efficient, as doing so with the least amount of time and resources. Achieving this requires decomposition of the supply chain design problem to a manageable size while ensuring that all significant interactions are covered, as well as suitable decision support, addressing the issues and propositions for supply chain design decision-making identified in the previous chapter.

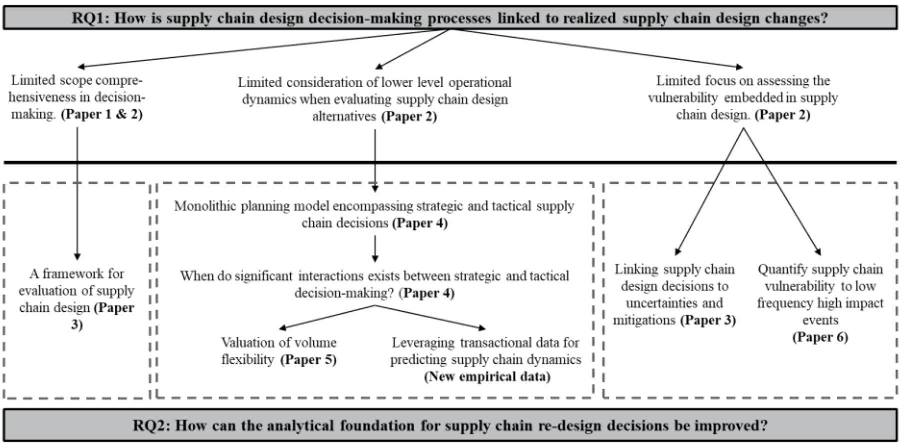

Figure 5.1: Link between RQ1 and RQ2.

As illustrated in Figure 5.1, and elaborated in the previous chapter, three central issues pertaining to effective supply chain design decision-making were identified. Following the emergent nature of the research, this chapter reflects the work done within the OEM to improve supply chain design decision-making. This work is reported in Paper 3 *(Supply Chain Costing: Beslutningsunderstøttelse for nye forsyningskonstellationer),* Paper 4 (*When to integrate strategic and tactical decisions? Introduction of an asset/inventory ratio guiding fit for purpose production planning*), Paper 5 *(Outsourcing of production: The value of volume flexibility)*, and Paper 6 *(An effect-oriented approach to assessing supply side vulnerability in global supply chains),* offering insight that improves the analytical foundation for supply chain design decision-making. Furthermore, empirical data not addressed in the four research papers are introduced regarding the leveraging of operational data for supply chain design decision-making. Table 5.1 outlines these contributions and their linkage to the literature streams informing supply chain design decisions.

Table 5.1: Contributions to the analytical foundation of supply chain design decision-making

Section:	Representative questions raised when evaluating supply chain design changes	Building on literature stream	Addressed in Paper
5.1 A framework for the evaluation of supply chain design	*"Are the impacts across all functions in the value chain quantified?"*	Cost accounting, Operational Modelling and Supply chain resilience	Paper 3
5.2 Interactions between strategic and tactical decisions • Valuation of volume flexibility • Predicting system behaviour using operational data	*"What is the value of being more flexible?"* *"What is the consequence of offshore supply with long lead-times?"* *"We need to be able to show the benefits of utilising a supplier of close proximity with just-in-time delivery compared to an offshore supplier."*	Operational Modelling	Paper 4 and 5 + new data
5.3 Supply chain vulnerability and supply chain design • Continuous uncertainty • Low-frequency high-impact events	*"What is the right balance between performance and risk?"* *"When are we getting too dependent on a supplier?"*	Supply chain resilience	Paper 3 and 6

This chapter builds on the previous chapter by advancing the analytical foundation for supply chain design in a context where changes relate to a subset of the full supply chain, and supply chain design decisions span numerous functional areas, with a project lead responsible for information search, analysis and consolidation before presenting this to senior management for decision-making (Moschuris, 2008; Wouters, Anderson, Narus, & Wynstra, 2009). The analytical foundation is made up by the set of decision support systems, accumulated analytical knowledge and guidelines which sets the frame for information search and analysis, allowing project teams to recommend a course of action and decision-makers to evaluate alternatives. Advancing the analytical foundation thus improves the procedural rationality of the decision-making process (Dean & Sharfman, 1993).

The first section addresses issues regarding the scope and comprehensiveness of information search in the decision process. This is addressed through the development of a conceptual model for analysing supply chain design (Paper 3). The second section discusses the decomposition of supply chain design decision-making and system behaviour by addressing when interactions between strategic and tactical decisions in the supply chain are critical (Paper 4). The second section dives even deeper into one such interaction by investigating how lower level tactical decision-making (volume flexibility) influences higher-level strategic decision-making (outsourcing decision). This is investigated by testing the ability of decision-makers to accurately valuate volume flexibility in cost-driven decision-making (Paper 5). Furthermore, reflecting the importance of strategic-tactical interactions, it is shown how transactional data can be leveraged for predicting supply chain system behaviour when changing the supply chain design. Following this, improvements in the assessment of supply chain vulnerability embedded in the supply chain design (Paper 3 and 6) is addressed.

5.1. A FRAMEWORK FOR THE EVALUATION OF SUPPLY CHAIN DESIGN

In the analysis of decision-making processes and their outcome in Chapter 4, it was shown how limited procedural rationality characterised decision-making. Lacking comprehensiveness of cost estimations negatively impacted decision-making effectiveness through unexpected consequences (i.e., cost estimation errors). Further, the scope of cost calculations and the need for a clear link to the profit/loss statement in the OEM created a mismatch between the strategic rationale behind intended supply chain design changes and realised changes. With decision-making decentralised across line functions, such as at individual factories or category teams, the impact of the higher-level behaviour of the supply network becomes elusive for the individual decision-maker. Unless receiving substantial managerial attention, this was prone to lead to biased decision-making (Asmussen, Kristensen, & Wæhrens, 2018; Asmussen, Kristensen, & Wæhrens, 2017). Senior and executive management focused on increasing the flexibility of the supply network and reducing complexity, though, e.g. outsourcing of production. However, the marginal contribution towards a more flexible manufacturing footprint or reduced complexity were not visible, when making local supply chain design decisions, such as evaluating make-or-buy or supplier selection. Creating a disconnect between the system behaviour desired and the outcome of supply chain design decisions.

Paper 3 proposed a conceptual model for evaluating supply chain design alternatives, to address such bias in decision-making, and improve the estimation ability for supply chain design decisions. A six-stage process for analysing supply chain design is proposed with the conceptual model. The following section extends and elaborates on this conceptual model and its contribution to improving procedural rationality.

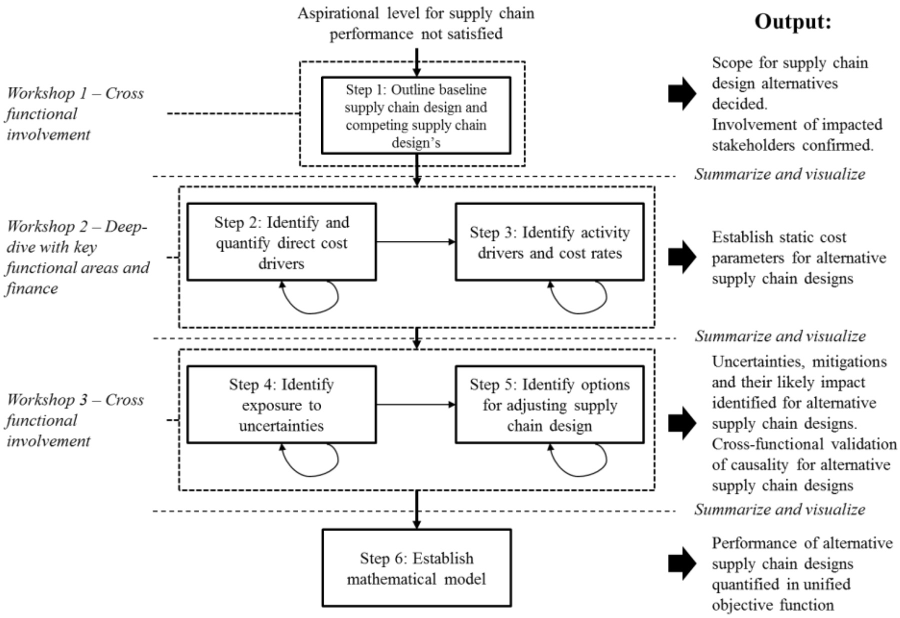

Figure 5.2: Process for the evaluation of supply chain design. Based on (Asmussen, Kristensen, & Wæhrens, Supply chain costing - Beslutningsunderstøttelse for nye forsynings-konstellationer, 2016)

Figure 5.2 illustrates the proposed process for analysing supply chain designs starting with compiling alternative supply chain designs and systematically identifying impacted stakeholders (Step 1), establishing static cost parameters for alternative supply chain designs (Steps 2-3), and understanding how these static cost assumptions cope with uncertainty (Steps 4-5). The process for analysing alternative supply chain designs thereby reflects the progression shown in Figure 2.1, from analysing cost factors building on cost accounting principles, to system behaviour, and the ability to cope with uncertainty and changes in the external environment. The focus of Steps 1-5 is to ensure scope comprehensiveness in the evaluation of the supply chain design, through systematic and cross-functional identification of variables significant for decision-making, and to achieve a joint understanding of the interactions across functional and hierarchical levels. Step 6 seeks to link these multidimensional variables in a mathematical model allowing for their joint assessment in a unified objective function. While this step has the potential to reduce the need for decision-makers to intrinsically asses and valuate both operational dynamics and real options embedded in the supply chain design, it requires specialised competencies and skills within mathematical modelling and a detailed understanding of supply chain behaviour. In the absence of such resources and capabilities, the five previous steps seek to reduce potential decision-making biases through a structured approach seeking the early involvement of cross-functional stakeholders, and thereby reduce the risk of cost estimation errors due to a narrow scope of cost calculations.

The process was tested in the OEM through a series of workshops. The first workshop aimed at broad cross-functional involvement to establish the current supply chain design, generating alternative supply chain designs, and to determine the overall scope of changes. Building on the cross-functional participation, potential dependencies across functions upstream and downstream are discussed and mapped to ensure the involvement of appropriate stakeholders. For the second workshop, the focus was on the detailed work of assessing cost impact. The third workshop focuses on reviewing these cost assumptions and subjecting them to a critical assessment by identifying uncertainty points and options for future adjustments.

The cross-functional involvement and use of visual representation of cost through the supply chain ensured a broad validation of cost scope and thereby contributed to reducing cost estimation errors. Table 5.2 elaborates on how the different steps mitigate biases in supply chain design decision-making based on existing literature and case evidence.

Table 5.2: Addressing biases in the analytical foundation for supply chain design.

Step	Decision bias observed in supply chain design decision-making:	Examples observed in supply chain design decision-making	Decision-making bias reduced by:
1	Disregard of relevant alternatives (Carter, Kaufmann, & Michel, 2007)	Decision-makers from manufacturing focused on the transfer of production between facilities, without considering outsourcing of production. Decision-makers from purchasing focused on supply chain design changes towards outsourcing, with limited regard for opportunities from utilising existing manufacturing setup. Using existing component supplier when outsourcing module assembly.	Ensuring cross-functional involvement in scoping of alternatives to avoid individual/functional availability biases. Enforcing the formulation of several alternatives imposes the search for alternatives outside the close proximity of existing supply chain design.
	Functionally focused decision-making process (Moses & Åhlström, Nature of functional involvement in make or buy decision processes, 2009)	Lacking involvement of functions across the supply chain impacted by decision-making, e.g., not considering financing cost/hedging cost, resulting in decision-makers wrongly assuming that all relevant information has been collected, and therefore stopping information search.	Ensure cross-functional commitment to scope, and determine the involvement of stakeholders based on differences between supply chain alternatives.
2	Relying on erroneous master data (Krægpøth, Stentoft, & Jensen, 2017)	Errors in master data leading to cost estimation errors.	Ensuring functional sign-off on critical cost drivers in cost estimations.

3	Bias towards measurable and visible cost drivers. (Wouters, Anderson, Narus, & Wynstra, 2009; Kirfchoff, Omar, & Fugate, 2016)	Complexity not considered in decision-making. Despite the strategic focus on reducing supply chain complexity, it is not valuated in decision-making.	Making a marginal increase in the cost of activities for sustaining the supply chain design explicit.
	Departmental thought worlds (Niranjan, Rao, Sengupta, & Wagner, 2014)	Different departmental perceptions of what is a 'reasonable' overhead cost.	Increasing transparency behind the cost of overhead activities.
	Use of standard costing for the allocation of overhead and indirect production cost. (Stentoft, Mikkelsen, Jensen, & Rajkumar, 2018)	Using average cost rates per factory not reflecting characteristics of activities.	Identifying the impact of relevant overhead activities and quantifying these based on activity cost rates.
4	Optimistic observation of uncertain outcomes (Carter, Kaufmann, & Michel, 2007)	No systematic identification of supply chain vulnerabilities and assessment of their potential impact.	Explicitly mapping uncertain variables and their impact on the supply chain creates an awareness of differences in the vulnerability of the alternative supply chain designs. Ensure cross-functional perspectives to capture uncertainties upstream and downstream in the supply chain.
	Stochastic variables treated as deterministic in the financial evaluation. (Christopher & Holweg, 2011)	Use of single-point forecasts for exchange rates and demand.	
5	Bias towards short-run performance predictions (Cyert & March, 1963).	Focus on the specific proposed supply chain design, not the behaviour of the proposed design or the possibility to adjust the design in the future.	Map differences in options for adjusting the supply chain design and the cost of these options. Creates awareness of the difference in *system behaviour* of the alternative supply chain designs.
6	Managerial difficulty in valuating supply chain system behaviour and interdependencies (Bansal & Moritz, 2015)	Difficulty determining the trade-off between improving volume flexibility, reducing supply chain complexity, reducing lead-times and direct costs, such as purchase price and labour cost.	Linking supply chain design differences to a unified objective function, in which supply chain design attributes determine the system behaviour of the supply chain, which is translated into cost performance through, e.g., capacity utilisation and cost of capacity adjustments.
	Decision driven by monetary performance differences (Wouters, Anderson, Narus, & Wynstra, 2009)	Supply chain design differences not quantified in monetary terms are easily ignored or challenged, favouring differences that can easily be quantified, such as purchase price, transport cost or labour cost.	

The conceptual model improved the procedural rationality in the evaluation of alternative supply chain designs, thereby reducing the exposure to decision-making biases potentially impairing supply chain design decisions. However, with the structured approach, new questions regarding *'what operational dynamics were relevant to include in the evaluation of alternative supply chains?'* and *'how could significant factors be included, considering the limited competences and resources for drafting complex mathematical models, as required by Step 6?'* This is addressed in the following section, which investigates the interactions between strategic and tactical supply chain decisions.

5.2. INTERACTIONS BETWEEN STRATEGIC AND TACTICAL DECISIONS

The hierarchical separation of decisions is generally associated with being an effective strategy for reducing decision-making complexity (Carter, Kaufmann, & Michel, 2007; Kaufmann, Michel, & Carter, 2009), as low interactions between decisions at different hierarchical levels enable decisions to be made in isolation, with an acceptable loss of optimality (Sethi, Zhang, & Zhou, 1992). Such assumptions of limited interaction between decision areas are seen both within the literature on production planning and control, e.g., MPC, ERP II, and supply chain design (Meixell & Gargeya, 2005). One example is inventory levels, which are generally perceived as tactical decisions managed independently from higher level decision-making, such as capacity investment decisions. However, capacity investments determine the physical structure, and thereby the frame for lower level inventory performance. However, existing research does not address when the hierarchical separation of decisions is associated with a substantial risk of hidden costs or sub-optimality.

Paper 4 makes some important contributions to the discussion on structuring supply chain design decision-making. First, the asset inventory (A/I) ratio, reflecting the relative importance of two different asset types in the supply chain, production assets and inventory, is introduced. Then, hierarchical and monolithic planning approaches are compared for various A/I ratios to distil insight into how firm and market characteristics influence the interaction between higher-level strategic decisions and lower level tactical decisions. These findings are summarised in Figure 5.3. For firms characterised by low A/I ratios, significant interactions appear between the hierarchically and functionally separated decisions. This carries considerable importance for the design of production planning and controls systems, with implications for supply chain design decision-making, as elaborated below.

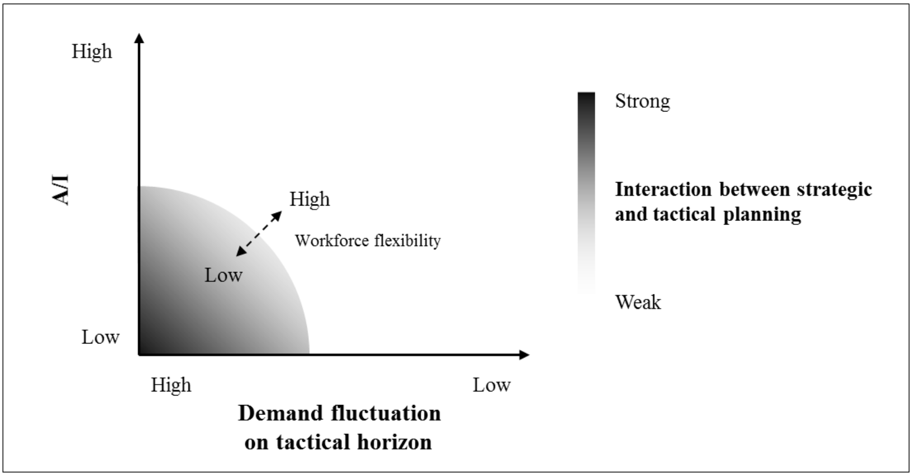

Figure 5.3: Firm and market characteristics linked to interactions between strategic and tactical decisions (Asmussen J. , Kristensen, Steger-Jensen, & Wæhrens, 2018).

For supply chains characterised by a low A/I value, higher level supply chain design decision-making, such as outsourcing or capacity location decisions, interacts with lower level tactical and operational decisions. The need for understanding these interactions, which are substantial for the resulting performance, increases decision-making complexity. The following example illustrates this complexity. A is a firm characterised by capital-intensive production equipment, stable demand with limited seasonality and a product portfolio of low value with a long shelf-life and low inventory holding cost. Oppositely, B is characterised by limited capital equipment, strong seasonality, and a product portfolio with a limited shelf life and high inventory carrying cost. In decisions regarding the design of the two supply systems, system A would be primarily concerned with ensuring the efficient utilisation of the costly production equipment, whereas the lower level tactical impact on flexibility and inventory levels is of limited importance for overall performance. However, for system B, the effect of tactical flexibilities, such as volume flexibility, becomes critical for the overall performance of the supply chain. The number of variables necessary to consider in the design of system B thus increases, as it is necessary to consider how the system will behave at the tactical level, with an impact on, e.g., inventory levels and workforce change costs. These decisions are typically treated as lower-level decisions, not considered when making structural decisions (Mieghem, 2003), while lower-level planning treats the production assets as fixed (Díaz-Madroñero, Mula, & Peidro, 2014). Strong interactions between strategic and tactical decisions (i.e. low A/I value), points to implications for supply chain design, as interactions between strategic decisions (e.g. capital investments) and tactical decisions (e.g. inventory or workforce planning) increase supply chain design decision-making complexity, through an increase in variables to be considered. Leading to the following proposition:

> **P5.1**: The A/I ratio is negatively correlated to supply chain decision-making complexity due to interactions across strategic and tactical decisions

If such interactions are not explicitly addressed it increases the risk of biased decision-making, either by ignoring lower level performance impact, or by relying on an intrinsic valuation of the effect prone to managerial biases (Niranjan, Rao, Sengupta, & Wagner, 2014).

Within the case company, senior management in PBU A and B indeed carried a strong perception that substantial performance benefits could be realised by increasing the flexibility of the supply network, primarily through an increased reliance on outsourcing. Despite the clear strategic intention with the outsourcing initiatives, the financial evaluation remained focused on direct cost drivers, such as material, labour, and transport costs, and did not incorporate any value from improved flexibility. Based on these cost elements, the financial evaluation typically showed a marginal cost increase. As the expected benefits could not be explicitly quantified using standard costing principles, they were not easily considered within other functions and hierarchical levels outside of manufacturing. This prompted senior managers within both R&D and purchasing to question why time and resources were spent on evaluating these supply chain design changes. A senior product design engineer expressed the following: *“Where is the money in this? If we look at the numbers, it is clear there is no saving. Being asked to do this just seems like a political decision”.* This attitude reflects both a strong reliance on the quantified elements in the financial evaluation and limited recognition of the interactions across functions and hierarchical planning levels not captured by standard cost accounting. This prompted an investigation of the value of such strategic-tactical interactions, to enable their valuation to be compared against immediately visible costs, such as purchase price.

5.2.1. VALUATION OF VOLUME FLEXIBILITY

Paper 5 leverages the monolithic model developed in Paper 4 to quantify the value of volume flexibility when outsourcing production and test decision-makers’ ability to intrinsically assess the economic value of volume flexibility. Although production outsourcing only concerns a subset of supply chain design changes, and volume flexibility is just one of several tactical dynamics related to changing the supply chain design, focusing on the interactions between outsourcing and volume flexibility was relevant, as the most frequent type of supply chain design change within the case company was production outsourcing, and volume flexibility remains a crucial driver for production outsourcing (Scherrer-Rathje, Deflorin, & Anand, 2014).

A contribution is made to existing literature, characterised by a limited understanding of the interaction between production outsourcing and volume flexibility (Wang, Chen, Wang, & Su, 2010) and the ability of decision-makers to economically valuate tactical elements, such as flexibility (Bansal & Moritz, 2015). As improving cost efficiency and the flexibility of the supply chain remain two of the most important drivers behind supply chain redesign (Krægpøth, Stentoft, & Jensen, 2017), the ability to economically valuate volume flexibility enables the determining of a trade-off between the two, rather than addressing them as sequential goals (Cyert & March, 1963) optimising one at the expense of the other.

As described, there was a clear perception within senior decision-makers, especially within manufacturing, that substantial value was nested within increasing volume flexibility. However, showcasing this value was obscured by complex interactions between decentralised decision-makers at different functional and hierarchical levels. Building on the literature reviewed in Paper 5 and interviews with factory managers, sourcing managers, production planners and logistics managers, the interaction between production outsourcing and volume flexibility is mapped in terms of range, time and cost (Slack, 1983) in Figure 5.4. As the monolithic model spans both investment decisions in production equipment, workforce adjustment, use of overtime and supplier constraints, it spans the interactions between production outsourcing and volume flexibility and thereby allows for the impact on volume flexibility to be quantified in economic terms through the objective function. Although the monolithic model does not explicitly address the production outsourcing decision as a decision variable, the hierarchical and functional span of the model could be leveraged to quantify the economic value of volume flexibility through numerical experiments.

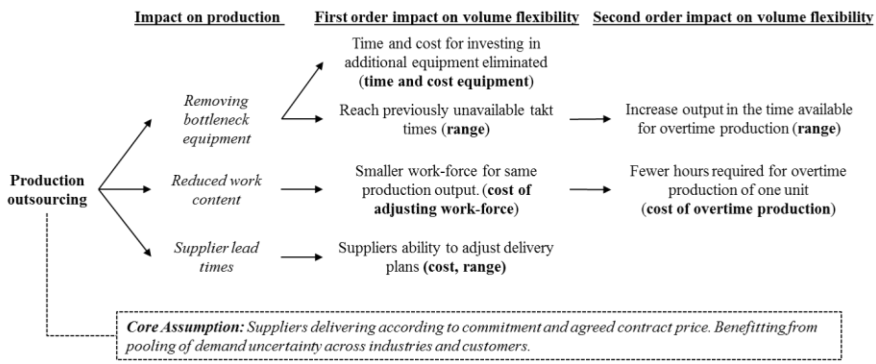

Figure 5.4: Impact of production outsourcing on volume flexibility (Asmussen, Kristensen, & Wæhrens, 2018).

Doing this for four different outsourcing cases within one factory in the OEM, and comparing the numerical results to actual decision-making, resulted in two contributions. First, it showed that the economic value of volume flexibility, in a production environment characterised by a low A/I value, on average corresponds to direct labour cost. This substantiates the importance of considering the impact of lower level tactical elements on higher level strategic decision-making. Something that is mostly ignored in cost models for the financial evaluation of production outsourcing (Ordoobadi, 2005; Gylling, Heikkilä, Jussila, & Saarinen, 2015; Ferreira

& Prokopets, 2009; Kumar & Kopitzke, 2008). Furthermore, it points to a risk of suboptimal decision-making if the financial evaluation of supply chain design changes is resting only on observable costs, which can be validated by the finance function and linked to the profit and loss impact. The risk of suboptimal decision-making is thus profound, when the value of unobservable system behaviour, is on par or exceeds other cost factors (i.e., labour cost and purchase price), which are attributed a high level of significance. The numerical experiments show that this is the case for volume flexibility in supply chains characterised by a low A/I value. Second, as illustrated in Figure 5.5, the value of volume flexibility is situational, being dependent on the specific characteristics of the outsourcing case, and the fluctuation in demand. The high coefficient of variance (CoV) of the value of volume flexibility relative to labour cost suggests a substantial difficulty for decision-makers to intrinsically valueate flexibility. The monolithic model thus enables decision-makers to reduce their reliance on an intrinsic valuation of complex system behaviours, and translate strategic intentions to a comparable unit, i.e., cost, and thereby decreasing bias in decision-making.

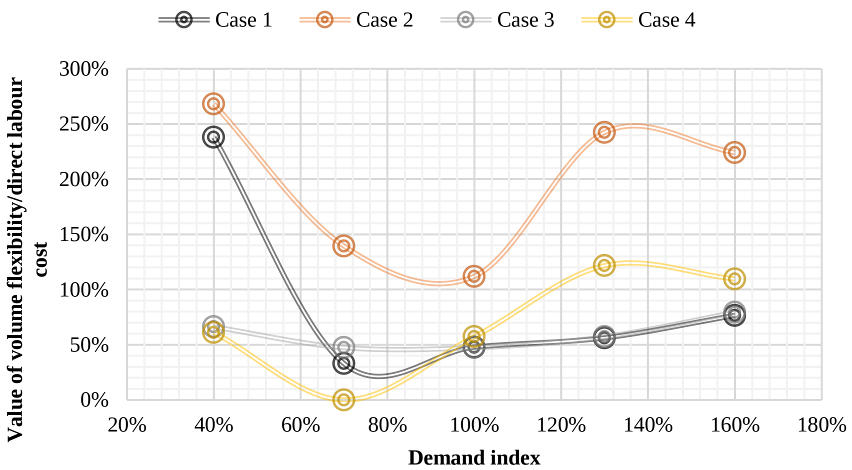

Figure 5.5: Value of volume flexibility from outsourcing relative to direct labour cost in outsourced activities

The results substantiate the importance of Step 6: mathematical modelling in the conceptual model presented in Section 5.1. However, considering that the systematic use and anchoring of mathematical models in the industry remain poor (Buxey, 2005; Lund & Raun, 2017) and the need for decentralised decision-making, issues remain for improving the analytical foundation of supply chain design decisions.

The following section addresses a different approach to improve the analytical foundation and reduce supply chain decision-making complexity by leveraging operational data for supply chain design decision-making.

5.2.2. PREDICTING SYSTEM BEHAVIOUR USING OPERATIONAL DATA

At the case company, when discussing changes in the location of suppliers and manufacturing sites as part of supply chain design changes, a recurring topic remained the impact of changing location on inventory levels. Decision-makers were of the intuitive understanding that extending the geographical distance between supply and demand would carry an additional cost regarding an increase in on-hand inventory levels and goods in transit inventories. This problem of managing inventory has received abundant attention in operations management and operations research (Bertrand & Fransoo, 2009). Typical perspectives include the choice of ordering policy, order quantity, and safety stock. However, as discussed in Section 2.2.2, inventory decisions are rarely in scope for supply chain design decisions, as managing inventory is a lower level operational activity, concerned with optimising within the overarching structure. However, neglecting the impact of supply chain design decisions on inventory levels opens up the possibility that a substantial increase in inventory carrying cost offsets other performance improvements, e.g., lower labour cost. Indeed, inventory holding cost is associated with significant hidden cost (Gylling, Heikkilä, Jussila, & Saarinen, 2015; Gray, Skowronski, Esenduran, & Rungtusanatham, 2013).

Several limitations were observed in the case company regarding applying existing methodologies for determining the impact of inventory levels when decentralised decision-makers needed to estimate the effect on inventory levels, e.g. if considering to move production from country a to b. These challenges relate to operational data (e.g., lead-time uncertainty and order quantities) not being available for new supply chain design alternatives and functional separation of data, making it difficult for the decentralised decision-maker to obtain all the relevant data, even when historical data did exist.

These challenges were observed to lead to a simplistic behaviour either by ignoring the operational impact on inventory and service level or with the impact being addressed by solely looking at goods in transit, thereby ignoring the impact on cycle-stock and safety stock. To mitigate this and increase both the comprehensiveness and accuracy of the analytical foundation underpinning decision-making, it was tested whether historical transactional data could be leveraged to improve the accuracy of supply chain design decisions without increasing the time and effort required by decentralised decision-makers.

The initial assumption was that lead-time would be a predictor of resulting inventory levels. Such a prediction builds on the logic that a long lead-time indicates a long geographical distance to the supplying location, whereby order quantities would be high to ensure cost-efficient transport, and thereby also increase cycle-stock in the receiving entities. Similarly, when lead-time is extended, both demand and supply uncertainty is higher, resulting in the need for more safety stock.

This was tested using transactional data on the contractually agreed lead-time recorded in the Material Requirement Planning (MRP) system and resulting inventory levels, measured in weeks of supply, for all item-plant relations across the case company.

Data were filtered to ensure that data relevant to the predictions were used. First, to ensure data reflecting ongoing operation, items that lacked continuous demand throughout the year, e.g., spare parts, newly introduced items, or items during phase-out, were filtered out. Second, it would be expected that operational buyers and logistics managers responsible for inventory levels would more carefully manage and attend to more costly items, as these would, all else being equal, carry more significance for financial measurements of inventory levels. Because of this attention, inventory levels would be managed more effectively, resulting in fewer days of supply. This assumption is confirmed by a linear correlation between *Item cost* and *days of supply* significant at the 0.001 level. In Figure 5.6, this linear relationship is depicted by the green line. Comparing the green line to the yellow line, reflecting a moving average, it is clear that a large group of items, valued below 300 EUR/item (reflected by the blue vertical line), are characterised by substantially higher inventory levels measured in days of supply. For the remaining items (above 300 EUR/item), the moving average remains stable, within 1-2 weeks of inventory coverage, suggesting that the underlying behaviour for inventory management is consistent for this price range.

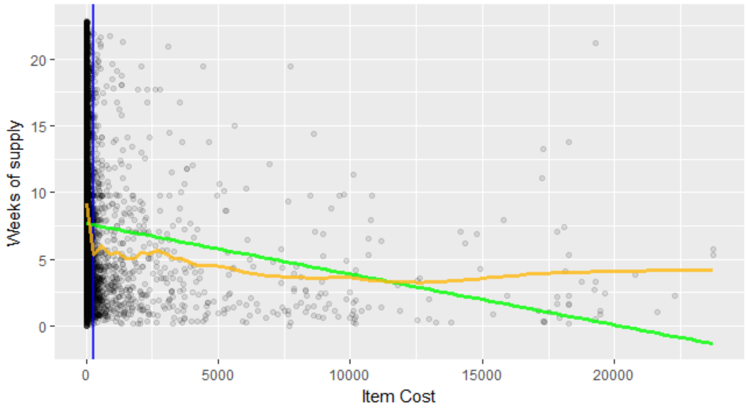

Figure 5.6: Relationship between item cost and weeks of supply for each item-plant relationship in the OEM's manufacturing network.

As it was the intention to use historical data to predict the performance of future supply chain designs, predictions should be based on the behaviour relevant for significant cost drivers, namely, items with a cost above 300 EUR/item. Although basing predictions on the right-hand side of the blue line in Figure 5.6 entails that inventory levels for low-cost items would be underestimated, this bias would be of less importance, as this underestimation concerns items of limited impact on overall inventory cost.

Although individual data points would be characterised by noise due to errors in data entry into the ERP system and periodic fluctuations in inventory levels, a clear pattern emerges between lead-time and inventory level, as depicted in Figure 5.7, when a centred moving average reduces the noise.

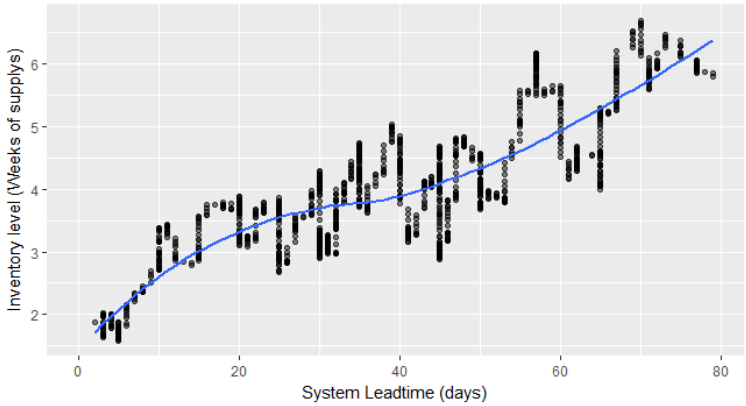

Figure 5.7: Relationship between system lead-time (negotiated/contractual) and inventory performance. Cantered moving average across 75 data points.

The data confirms the intuitive understanding that as lead-time increases, so does the inventory level. More importantly, the data could be leveraged for informing relevant trade-offs informing supply chain design decisions. If comparing a local supplier with a lead-time of 5 days to an offshore supplier with 70 days of lead-time, it would be predicted that future on-hand inventory levels would be close to 3 times as high for the offshore supplier; this impact on the lower level operational performance can then be translated to monetary value, and compared to, e.g., the price difference between the two suppliers. Indeed, Bozarth et al. (2009) suggest that increasing supply chain complexity, such as by extending lead-times, could be beneficial if it allows the focal company to achieve a competitive advantage through alternative means, e.g., lowering the purchase price. By leveraging the historical data, decentralised decision-makers in the case company were better equipped to judge and justify such trade-offs, thereby contributing to moderating the impact of supply chain decision-making complexity on decision-making effectiveness.

The noise in the data suggests issues if the expectation was to make precise predictions on the future inventory level of an individual item. However, with supply chain design decisions concerning 50-100 items or more, errors in the prediction of individual items would level out across the population. In this way, existing transactional data can be leveraged to act as a feedback loop for higher-level strategic and tactical supply chain design decisions (Meixell & Gargeya, 2005). At the same time, it offers a significantly simplified approach, allowing lower level interactions to be estimated by decentralised decision-makers, without the use of sophisticated mathematical modelling or simulation encompassing multiple tiers of the supply chain (Melo, Nickel, & Saldanha-da-Gama, 2009; Klibi, Martel, & Guitouni, 2010).

Within the OEM, the described approach served to reduce supply chain design decision-making complexity and improve decision-making effectiveness. First, it increased comprehensiveness through explicitly considering the detrimental effect of extending lead-time on on-hand inventory performance and making such performance effects visible for strategic purchasers, who usually are detached from daily operations. Therefore, it became possible for decision-makers to explicitly consider trade-offs, e.g., between price reduction and lead-time increase, without relying on intrinsically estimating the value of the latter or relying solely on the former due to its objective and quantifiable nature. Second, the approach reduced the effort required to estimate the impact, allowing predictions to be made for supply chain redesign cases concerning several hundred different items. Furthermore, having a direct effect on supply chain design decision-making practice, the approach to leveraging transactional data carries two additional implications. First, it provides insight into how to organise and support supply chain design changes, which will be further discussed in Chapter 6. However, a brief remark is added here, on the necessity to have centralised analytical resources with strong supply chain understanding who can collect, analyse and convincingly anchor such empirical-based decision support across the organisation to increase the effectiveness of functionally and hierarchically separated decision-makers. Second, many supply chain problems have been approached from the point of logical and analytical tractability, including inventory management (Bertrand & Fransoo, 2009). However, increasing data availability and information processing power suggest that empirical approaches, like the one presented and discussed above, can offer a different perspective on classic operations problems. Building on data that reflects the underlying behaviour of humans and systems in the supply chain, rather than an idealised world of rational agents, such approaches can be more relevant for informing complex decisions.

5.3. SUPPLY CHAIN VULNERABILITY AND SUPPLY CHAIN DESIGN

Considerations of supply chain resilience are a critical element in supply chain design (Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2011). However, as outlined in the analysis of decision-making practice (Chapter 4), explicit considerations of supply chain vulnerability and the matching with appropriate supply chain designs, as suggested by Pettit et al. (2010), received only limited attention within the OEM. When supply chain vulnerability was being addressed as part of supply chain design decision-making, it was treated in an ad-hoc manner or through generic policies, often leaving decision-makers ill-equipped to assess the vulnerability embedded in the supply chain designs upon which they are deciding. As an example, one purchasing manager expressed the lack of guidelines on "*how to consider different levels in exposure to foreign exchange rates when comparing alternative supply chain designs".* Similar questions were asked regarding the level of exposure towards a given supplier or factory, compared to the benefits of accepting a high vulnerability.

Two contributions were made to improve managerial understanding and consideration of supply chain vulnerability in supply chain design decisions. These two contributions relate to the type of uncertainty faced, either continuous or discrete.

5.3.1. CONTINUOUS UNCERTAINTY

As already introduced with paper 3, a methodology for matching the supply chain design with relevant uncertainties and real options embedded in the supply chain design was presented. The contribution of the conceptual model is its guidance for decision-makers in breaking down the supply chain into its entities, and the associated uncertainties, vulnerabilities and real options. This understanding of uncertainties constitutes a first step in explicitly considering the resilience of the supply chain in supply chain design decisions. Making the impact of such uncertainties clear, by using historical data or predictions of future developments (as discussed in Section 5.1), addresses high-frequency events, in which both the probability distribution and consequences can be established, or historical data offers meaningful insight for decision-makers.

This view, however, encapsulates neither the low likelihood nor severe consequences of low-frequency high-impact events, such as the 2011 earthquake and tsunami in Japan, which severely disrupted global supply chains. The following section builds on Paper 6 to introduce a model for considering such low-frequency high-impact events in supply chain design decision-making.

5.3.2. LOW-FREQUENCY HIGH-IMPACT EVENTS

The potential range of disruptive events occurring along the interconnected global supply chain is countless. Paper 6 builds on the understanding that bounded rational decision-makers are incapable of identifying and computing accurate probabilities for all potential events, resulting in a disruption of the supply chain. Instead of working from the perspective of the individual event, as is typical in supply chain risk management practice, Paper 6 presents a model for assessing the vulnerability embedded in the supply chain design by quantifying the probable maximum loss (PML) if a node in the supply chain is disrupted. As such, the focus of interest is not the event itself, i.e., whether it is a bankruptcy of a supplier, factory fire or earthquake that disrupts one or more nodes in the supply chain. Rather, it is the consequences to the supply chain if such a *worst-case* event occurs that is of interest. Such a worst-case event can be reflected by the residual between the time the supply chain can sustain its output and the time it takes to recover supply. Figure 5.8 offers a conceptual view of the logic behind the PML model as the residual between time to recover (TTR) and time to survive (TTS).

- Time to recover (TTR): Denotes the time to re-establish supply and is primarily driven by the technical and commercial complexity of the items being supplied by the disrupted entity, as well as the structure of the supply market.
- Time to survive (TTS): Denotes the time within which the supply chain can operate based on on-hand inventories and goods in transit without a loss of

output due to the disrupted node. Time to survive thus reflects decisions regarding strategic safety stock and supplier dependencies.

In this way, the PML model combines product characteristics with the structure of the supply chain, by leveraging transactional data on on-hand inventory levels and goods in transit with final customer demand, to quantify the negative consequences of a worst-case event disrupting a node in the supply chain.

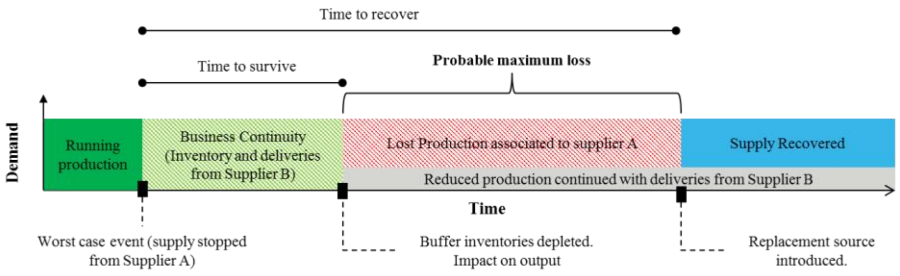

Figure 5.8: Conceptual overview of Probable maximum loss from disruption of supply entity (Asmussen, Kinra, Uhre, & Lund, 2016)

For TTR < TTS, there is no residual risk embedded in the supply chain design, but with TTR > TTS, there is a residual risk reflecting a potential loss if a node in the supply chain is disrupted. TTS can be reduced by either adjusting supply chain dependencies, e.g., the introduction of a dual source, or an increase of strategic buffers. Alternatively, actions can be taken to reduce TTR, e.g., through the use of standardised items that can be sourced from alternative suppliers or changing component tolerances, thus reducing the time taken to ramp-up new production. The PML model thus encompasses both dimensions of supply chain resilience as discussed in 2.2.1. Robustness is reflected through, e.g. investments in safety stock, and agility through, e.g. investments in reducing the time for introducing a new supplier.

The contribution of the PML model lies in the transparency it offers towards critical vulnerability points in the supply chain, without decision-makers needing to identify and accurately estimate the probability function of a vast array of low-frequency high-impact events prone to estimation bias (Carter, Kaufmann, & Michel, 2007). Drawing the Pareto frontier for the supply chain design, reflecting different alternatives for product design (TTR), use of strategic inventory (TTS), and allocation of sourcing split to different suppliers (TTS) assists decision-makers by making visible the trade-offs between the use of different policies for ensuring supply chain resilience. By establishing the cost function for the various design variables, decision-makers can compare the vulnerability of different supply chain designs in a trade-off against cost performance.

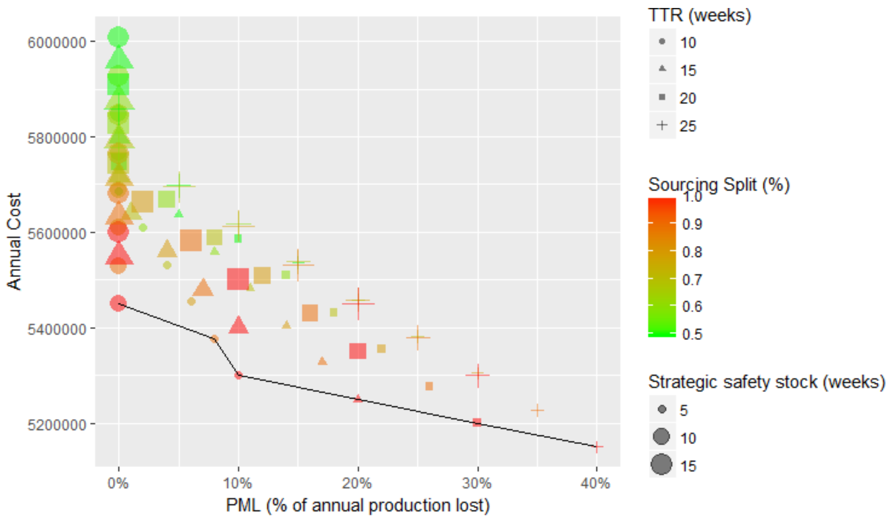

Figure 5.9: A Pareto frontier for alternative supply chain designs reflecting supply chain vulnerability (PML) and annual cost

A representative numerical experiment is shown in Figure 5.9 to illustrate the contribution to the supply chain design problem. The mathematical notation and details behind the numerical experiment can be found in Appendix B. Figure 5.9 shows the solution space and the Pareto frontier for the supply chain design decision. It thereby reflects the underlying trade-off between supply chain vulnerability and cost, when balancing the three design variables:

- Investing in changing the product design to reduce TTR.
- Adjust the volume split between several suppliers, thereby facing reduced volume discounts.
- Introduce safety stock of components facing a higher inventory holding cost.

The Pareto frontier thus supports the formulation of supply chain design policies by depicting the trade-off between supply chain vulnerability and cost performance. In the specific numerical experiment it is shown that the level of supply chain vulnerability can be reduced by 50%, from a PML of 40% of annual production lost to 20% of annual production lost, while increasing total cost by less than 2%, whereas reducing PML from 10% to 8% would increase annual cost by 1.4%. This offers decision-makers a foundation for judging cost versus vulnerability, based on the actual decision-making situation and supply chain characteristics, instead of relying on generic policies, such as *"within our category team, we generally work by mitigating risk by operating with a dual-source"* (Sourcing manager, procurement). This similarly offers decision-makers a foundation for judging cost versus vulnerability. Additionally, it points to the need for a cross-functional understanding of interdependencies, as TTR is mostly dependent on product and process requirements, determined in the new product development project, while the costlier strategic safety stock is deployed when it becomes evident that supply chain managers are not confident with the existing vulnerability levels.

5.4. SYNTHESIS

In this chapter, the focus has been on advancing the analytical foundation for supply chain design decision-making based on action interventions within the case company.

Consistent with recent research pointing to the importance of accurate and relevant costing information (Krægpøth, Stentoft, & Jensen, 2017), the work presented in this chapter provides specific guidance on how firms can improve the analytical foundation underpinning supply chain design decision-making, and addressing the issues identified in Chapter 4.

The tools and methods developed here do not provide an exhaustive suite of decision support but focus on specific improvements and interventions conducted to address specific needs within the case company. These contributions improve the procedural rationality of supply chain design decision-making (Dean & Sharfman, 1993) while reflecting the perspectives and challenges faced by decision-makers. On top of these ‘practical’ contributions, the results presented in the chapter also present generic knowledge complementing and extending existing literature. In summary, contributions have been made with regards to the:

- Development of a conceptual model and process for evaluating supply chain design reflecting that supply chain design decisions are partial and decentralised, and susceptible to scope errors in cost estimations.
- Generation of insight into the partitioning of supply chain design decision-making. With the introduction of the A/I ratio, insight is generated into when strategic and tactical supply chain decisions should be integrated.
- Development of a monolithic model integrating strategic and tactical planning decisions relevant for supply chain design decision-making.
- Demonstration of the applicability of the monolithic planning model in informing supply chain design decisions, by enabling valuation of volume flexibility in production outsourcing.
- Applicability of leveraging transactional data for informing supply chain design decision-making, thus mitigating the effect of supply chain decision-making complexity on decision-making effectiveness.
- Development of a supply chain vulnerability model for addressing low-frequency high-impact supply chain disruptions by linking supply chain design decisions to a measure of vulnerability, which does not rely on the limited ability of boundedly rational decision-makers to identify and accurately estimate the probability of a vast array of infrequent events (Kaufmann, Michel, & Carter, 2009).

The interactive work of developing and enacting the improvement in the analytical foundation was conducted primarily from the end of 2014 to the end of 2016, as shown in Figure 3.1. Table 5.3 summarises the change in the analytical foundation underpinning supply chain design decision-making in the OEM and how this influenced decision-making.

Table 5.3: Development of the analytical foundation and its impact on decision-making practice

	2014	2015	2016	2017
Cost accounting	No systematic approach for evaluating supply chain design alternatives.	A standardised approach for addressing direct cost introduced.	Development of ABC costing for supply chain sustaining activities.	ABC costing applied in the majority of supply chain design changes.
System Behaviour	Not addressed in the majority of decisions. Assessment of capital tied up in transit in a few cases.	Introduction of approach for assessing inventory impact when extending lead-time.	Impact of inventory profile assessed in the majority of supply chain design changes.	
Supply chain resilience	Relying on category policies, e.g. use of dual-sourcing for this commodity type.		Some assessment of vulnerability to changing exchange rates, demand patterns or critical dependencies.	
Difficulties raised during the decision-making	"Why are the cost baselines different?"	"Have the impact on inventory been considered. How much more will it cost when our lead-time is getting longer?"	"What is the cost of sustaining all of these activities in-house?"	"How is the optimal balance between the dependency in our different key supply locations?"

The structured assessment for evaluation of supply chain design alternatives, as introduced by Paper 3, and the leveraging of operational data for predicting system behaviour gained widespread application. These methods have thus formed the analytical foundation for most supply chain design decisions made from 2016 and onwards. In 2015, the impact of extending or shortening lead-time in the supply chain was thus a substantial concern during decision-making and a source for cost estimation errors. Following the development and anchoring of decision-tools, which leveraged the analysis of transactional data to predict the impact of lead time on system behaviour, this factor contributing to decision-making complexity was mitigated. Subsequently, decision-makers focused their attention on the cost associated with sustaining a given supply chain design. Work was then done to extend the standardised approach for comparing supply chain design alternatives, to include supply chain sustaining activities (ABC costing). With the anchoring of such practice, it again allowed decision-makers to make complex trade-offs and thereby mitigate the effect of supply chain decision-making complexity. Throughout the period, the continued development and anchoring of the analytical foundation contributed to an increasing ability to accommodate supply chain decision-making complexity, leading to the proposition:

> ***P5.2:*** *Continued development and use of an analytical foundation diminish the detrimental impact of supply chain decision-making complexity.*

There were apparent differences in the level of penetration of the different interventions undertaken to improve the analytical foundation as depicted in Table 5.3. The more advanced aspects, related to operational modelling of the supply chain, e.g. the application of the monolithic model for evaluating specific supply chain design alternatives, was applied less frequently, and primarily by the researcher. Similarly, the PML model achieved limited penetration into supply chain design decision-making. While several reasons can be identified for the different penetration levels of the decision-support tools, the findings reflect the difficulty of transitioning from addressing supply chain design based on observable 'facts' to an uncertain future as reflected in Figure 2.1, despite strong perceived needs for such considerations in decision-making. Leading to a second proposition regarding the analytical foundation:

> ***P5.3:*** *The analytical foundation for supply chain design is gradually building from understanding an observable path to reflecting behaviour in an uncertain future.*

This proposition points to the importance of learning and gradually developing the supply chain design capability, and an organisational design supporting such a development.

Figure 5.10 summarises the three propositions synthesised from this chapter, adjacent to the findings from Chapter 4.

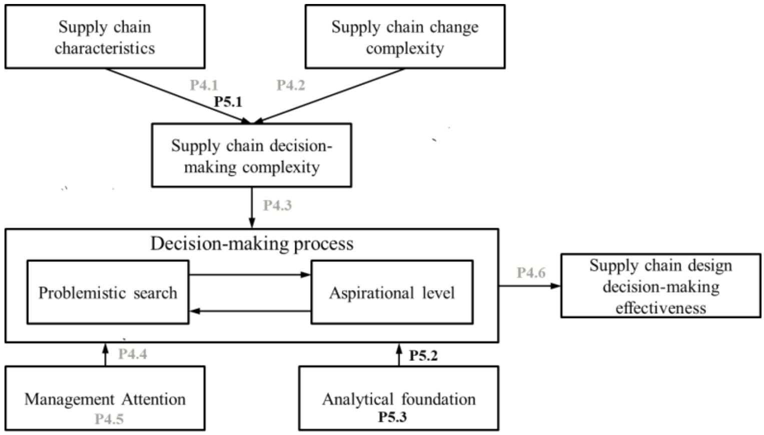

Figure 5.10: Identified propositions from Chapter 5 marked with black. Propositions from Chapter 4 in grey.

CHAPTER 6. ORGANISING THE SUPPLY CHAIN DESIGN TASK

The previous two chapters have investigated *how supply chain design decisions unfold and are linked to realised changes* (Chapter 4), underpinning the role played by supply chain complexity, and *how the analytical foundation underpinning supply chain design decisions can be improved* (Chapter 5) to cope with complexity during supply chain design decision-making and reduce bias and errors in decision-making. The former reflected on how complexity increase the information processing need for supply chain design decision-making and the consequences of this, while the latter proposed specific interventions to improve the information processing capacity for supply chain design. Effective supply chain design decision-making would require a fit between the two. If decision-making complexity exceeds the analytical capability of the organisation, it induces the risk of erroneous decision-making (Manuj & Sahin, 2011). On the other hand, it should also be noted that if the analytical capability of the organisation exceeds the difficulty of decision-making, the organisation deploys and maintains excessive resource for information search and analysis, which is not adding value. This problem of balancing information processing need with the information processing capacity is normally treated as an organisational design problem (Galbraith, 1974).

In Chapter 4, the link to organisational design was implicitly made through the identification that supply chain characteristics such as the number of items or suppliers, increased decision-making complexity through the number and heterogeneity of stakeholders impacted by a decision (proposition 4.1). While in Chapter 5, the findings point to the need for the continued development of an analytical foundation supporting decentralised decision-makers (proposition 5.3). Building on these findings, a more detailed investigation of the organisation of the supply chain design task is undertaken in this Chapter, by addressing RQ3: *How does organisational design influence the supply chain design task?* The IPV is utilised as a frame for addressing the research question by investigating how the organisation of actors[3] within purchasing and supply management (Bals, Laine, & Mugurusi, 2018), influence the information processing need and capacity for supply chain design, and thereby the effectiveness of supply chain design changes, as depicted in Figure 6.1

[3] The primary actors were logistic managers located within each factory and category managers from the global purchasing department.

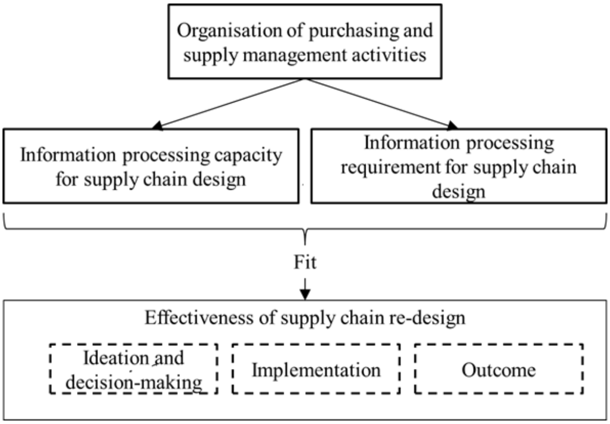

Figure 6.1: Link between the organisation of purchasing and supply management activities and supply chain design effectiveness.

The chapter thereby seeks to advance existing literature which primary have addressed the organizational design of supply chain design decision-making, through the participants in decision-making processes (Moschuris, 2008; Moses & Åhlström, 2009; Moses & Åhlström, 2008) or the impact of managerial involvement (Wouters, Anderson, Narus, & Wynstra, 2009).

The chapter builds on Paper 7 (*The impact of organisational complexity on supply chain redesign: An information processing view)*, which leveraged the differences in organisational complexity of purchasing and supply management between PBU A and PBU B.[4] The chapter thereby zooms out from the perspective of the individual decision to the patterns across supply chain design decisions and organizational units.

6.1. THE ORGANISATION OF SUPPLY CHAIN DESIGN IN PBU A AND B

Within the OEM, purchasing and supply management activities have been organised following a hybrid structure (Bals, Laine, & Mugurusi, 2018) with operational buying activities conducted locally, while strategic sourcing, is undertaken by centralised category management teams. These category teams span all three PBUs in the OEM. Purchasing and supply management activities, including the supply chain design task, are thus organised according to the same design principle across the case company. However, while activities are organised according to the same organisational design principles, the PBU A and B reflect different levels of organisational complexity due to differences in product design characteristics and historic supply chain design

[4] PBU C is excluded in this analysis, due to the low number of supply chain design changes conducted.

decisions; primarily the allocation of products creating interdependencies across the manufacturing networks.

Social network analysis (Wichmann & Kaufmann, 2016) of the actors and their interaction patterns within purchasing and supply management, was used to reflect the organisational complexity. Figure 6.2 depicts this analysis, showing how a dense network of interconnected actors characterises PBU A, while PBU B is characterised by more focused and independent groups of actors. PBU A, in turn, spanned actors, which were more interconnected compared to PBU B. This is despite the overall network characteristics such as the number of factories (six factories) and purchasing stakeholders (PBU A: 73, PBU B: 62) at the network level is similar for the two PBUs.

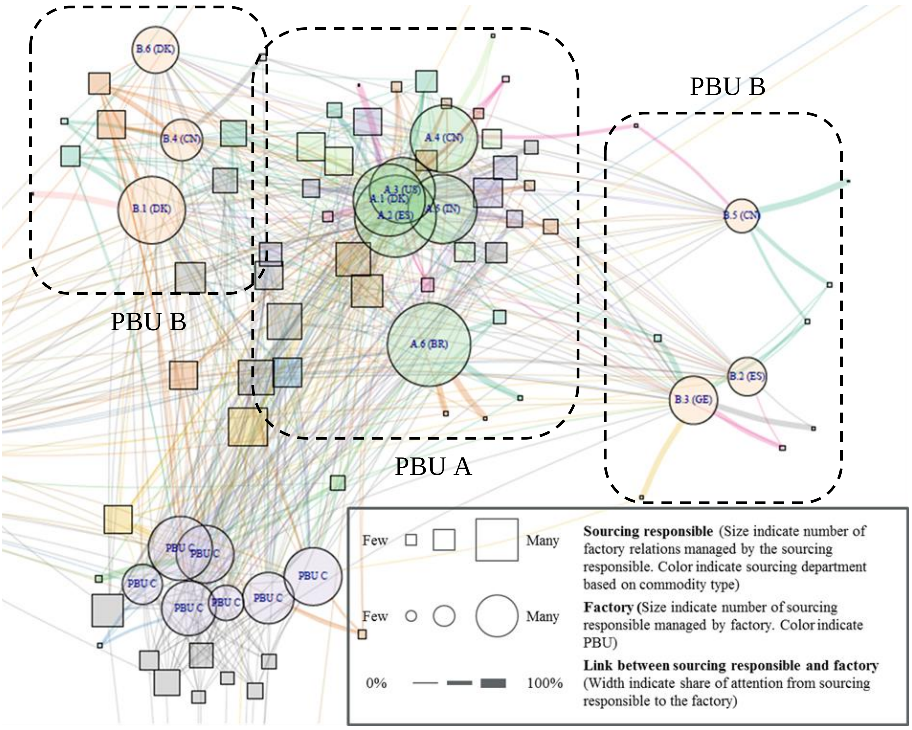

Figure 6.2: Social network analysis of organisational linkages between purchasing and supply management actors in the OEM.

6.2. IMPACT OF ORGANISATIONAL COMPLEXITY ON SUPPLY CHAIN DESIGN

In light of the above-mentioned differences in organisational characteristics, it was possible to analyse how organisational complexity influence supply chain design and the effectiveness of supply chain design. Table 6.1 summarises the analysis presented in Paper 7, based on 44 supply chain design changes conducted within PBU A and PBU B in the timespan covered by the thesis[5]. The analysis reveals how the organisation of PSM has a two-fold impact on the effectiveness of supply chain design.

The complexity of PSM was found to increase the information processing need for supply chain design, through reciprocal relations, increase in the number of and heterogeneity of stakeholders, and need for balancing local and global needs. All requiring non-standard information exchanges. Ceteris paribus, this would reduce the ability to implement supply chain design changes. These findings substantiate that the number of impacted stakeholders, rather than the number of items, is a driver of supply chain decision-making complexity (Asmussen, Kristensen, & Wæhrens, 2018). However, project teams and decision-makers also have substantial potential for influencing the information processing requirement for supply chain design. In PBU B, the project teams thus worked to deliberately scope the supply chain design changes to span few stakeholders, to reduce complexity and enable more rapid decision-making and implementation. These efforts to reduce complexity was the result of accumulated learning developed through the execution of several supply chain design changes in PBU B.

[5] The number of supply chain design decisions deviates from the sum across all factories in PBU A and B in Figure 3.1. The deviation is due to supply chain design decisions concerning several factories are counted as one here, while Figure 3.1 depicts the number of supply chain design decisions related to each factory.

Table 6.1: The impact of organisational complexity on supply chain design

Dimension	Sub-dimension	PBU A	PBU B
Organizational Complexity of Purchasing and Supply Management	Network structure	Parallel	Sequential
	Factories	6	6
	Category managers	73	62
	Suppliers	1,323	1,235
	Purchased items	8,847	16,386
	Avg. category managers per factory	45.6	28.5
	Avg. suppliers per factory	372	284
	Avg. purchased items per factory	3486	3540
Information processing need for supply chain design	*Stakeholders involved*	Typical 2-4 category management teams and 3-4 factories globally distributed	Typical 1-2 category management teams and 1-2 factories.
	Dependencies:	Unexpected reciprocal dependencies, e.g. dependencies through global volume commitments, requiring non-standard information exchanges.	Pooled or sequential dependencies in projects, e.g. transfer of production from sending to receiving factory.
Information Processing capacity for supply chain design	*Learning*	Limited learning as the dense network of relations results in the supply chain design task being distributed across more than 15 category managers. Resulting in a low task frequency for each individual, and poor possibilities for accumulating experience.	Substantial learning supported by the more focused network with the supply chain design task being distributed across four primary stakeholders. Resulting in a high task frequency for each individual, allowing an ongoing accumulation of task experience.
	Lateral relations	Existing low-intensity relations, with limited interactions and routines for collaborating.	Well established relations with frequent and close interactions through which existing routines for collaboration have been developed and anchored.
Supply chain design effectiveness (Low: 1, High: 3)	*Ideation and decision-making*	Mean: 1.98 Standard deviation: 0.7	Mean: 2.78 Standard deviation: 0.5
	Implementation	Mean: 2.1 Standard deviation: 0.9.	Mean: 2.95 Standard deviation: 0.21
	Outcome	Mean: 2.33 Standard deviation: 0.5	Mean 3.0 Standard deviation: 0

The complexity of PSM similarly impacted the information processing capacity for supply chain design. The large number of lateral relations in PBU A resulted in distributed learning, with no evident anchoring of practice. Neither was the large number of lateral relations able to accommodate the more complex redesign task.

Oppositely, in PBU B, learning was evident, and supply chain design changes were effectively executed within the frame of existing lateral relations.

For PBU A, the task to be executed were not only more complex, the information processing capacity for executing the task were also lower compared to PBU B. Thereby suggesting a better fit between the information processing capacity and need within PBU B relative to PBU A. This is reflected in the difference in effectiveness of the supply chain design task between the two PBUs.

This performance difference in the supply chain design task, have derivative implications. From Chapter 4 it was evident that the potential reduction in supply chain complexity was dependent on the complexity of the changes to the supply chain design, and supply chain complexity was prone to increase if not explicitly addressed (Asmussen, Kristensen, & Wæhrens, 2017). Further, as supply chain complexity increases, so do the organisational complexity of PSM, e.g. the addition of a local production entity increases the number of linkages within the PSM function. Increasing supply chain complexity is thus linked with an increasing organisational complexity of the PSM function, and thereby a diminishing ability to redesign the supply chain.

6.3. TASK EFFECTIVENESS IN THE DIFFERENT STAGES OF SUPPLY CHAIN DESIGN

From the assessment of task effectiveness, it is notable how task effectiveness increases as the supply chain design projects mature as depicted in Figure 6.3. This is partly explained by a selection mechanism, whereby lacking effectiveness at the decision stage, results in these supply chain design changes being less likely to move into an implementation and outcome stage, while those projects which are characterised by effective decision-making are more likely to move into the implementation and outcome stages. While there is no strong indication that the impact of organisational complexity is less significant for later stages of the supply chain design task, as the difference between task effectiveness in PBU A and B remained at a similar level across the three stages, it carries implications for research design as well as practice.

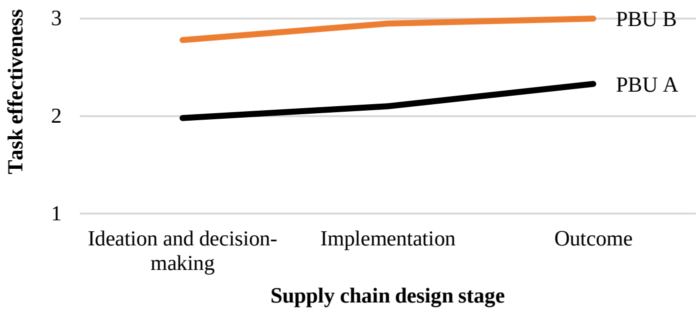

Figure 6.3: Task effectiveness of supply chain design in PBU A and B

Previous research on supply chain design decision-making has widely drawn on implemented changes as the unit of analysis (Larsen, Manning, & Pedersen, 2013; Johansson & Olhager, 2018). These findings suggest a significant selection bias if researching decision-making related to supply chain design based on implemented changes, as this unit of analysis ignores the difficulties and problems in the early stage of decision-making.

For practice, the findings suggest low effectiveness related to ideation and decision-making when organisational complexity is high. The low effectiveness points to issues with inefficient use of resources for information search and analysis and missed opportunities for improving the supply chain design. Issues which will not be visible through the exercise of monitoring formalised projects.

6.4. SYNTHESIS

From the analysis of how organisational design influence supply chain design novel insight is generated into the link between organisational design and supply chain design. These findings are summarised into four propositions.

> **P6.1:** *Supply chain characteristics influence the organisational complexity of purchasing and supply management activities through, e.g. the number of suppliers, the use of global suppliers, the number of production facilities and product allocations across these facilitites.*

> **P6.2:** *The higher the organisational complexity, the higher the decision-making complexity through the number of stakeholders in decision-making*

> **P6.3:** *The number and intensity of relationships between purchasing and supply management actors influence the information processing capacity of the organisation.*

P6.4: *Organisational complexity influences the allocation of appropriate management attention.*

These findings complement the findings from chapter 4 and 5 and extend the understanding of factors likely to influence the ability to redesign complex supply chains effectively.

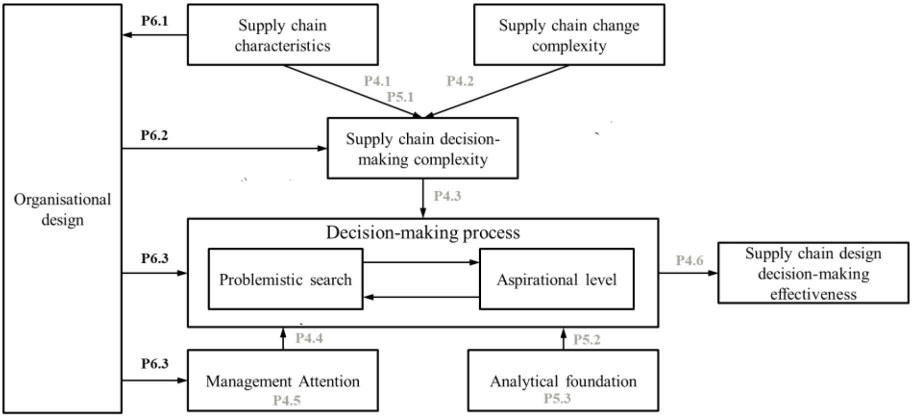

Figure 6.4: Identified propositions from Chapter 6 marked with black. Propositions from Chapter 4 and 5 in grey.

CHAPTER 7. CONCLUSION

The question of how to design the supply chain is in its very nature interdisciplinary and thereby spanning several theoretical domains. Similarly, an industrial journey towards improving supply chain design decision-making will span several functional areas and domains. The broad and multifaceted nature of the research domain, as well as the drive to simultaneously improve industrial practice, while developing new knowledge, shaped this thesis. It is also reflected in the three research questions, ranging from understanding how decision-making processes for supply chain design unfolds and are linked to realised outcome, to how to improve the analytical foundation underpinning supply chain design decision-making and lastly the organisation of supply chain design decisions.

As argued in the initial scoping of this thesis, the focus of existing research on supply chain design has primarily been working in three distinct directions (1) mathematical models for identifying an optimal solution, (2) different types of supply chain designs given particular contingencies and (3) the performance outcome of specific supply chain design changes. This thesis deviated from such research, by embracing the individual decision-maker in the process from initiation to implementation of supply chain design changes. Building on the BTF (behavioural theory of the firm) and IPV (information processing view), rather than RBV (resource-based view) or TCE (transaction cost economics), combined with the close interaction with the case company and the longitudinal study have allowed novel knowledge and practically relevant research contributions.

7.1. RESEARCH CONTRIBUTIONS

The thesis has covered a broad topic, making several distinct and complementary contributions. While these contributions are already highlighted through chapter 4-6 and in the individual papers, notable contributions are summarised below in relation to each research question:

RQ1: How is supply chain design decision-making processes linked to realised supply chain design changes?

- Improved the limited understanding of decision-making for complex group-based supply chain decision-making (Schorsch, Wallenburg, & Wieland, 2017), and specifically how supply chain characteristics influence decision-making effectiveness and behaviours of decision-makers. Thereby contributing to the stream of literature on supply chain complexity and decision-making (Bozarth, Warsing, Flynn, & Flynn, 2009; Schorsch, Wallenburg, & Wieland, 2017; Manuj & Sahin, 2011).
- Substantiated the link between supply chain decision-making complexity and cost estimation accuracy. Thus, confirming and extending existing research on outsourcing of IT-services into a supply chain context (Larsen, Manning, & Pedersen, 2013).

- Shown how the trade-off between monetary and non-monetary benefits increases decision-making complexity and introduces the risk of biased decision-making, resulting in increasing supply chain complexity unless a strong analytical foundation offsets it.
- Shown how management attention based on conflicting and coherent goals induces different behaviours influencing cost estimation accuracy, with the former being more effective in improving cost estimation accuracy. Pointing to the need for integration of management attention as a dimension in future research on strategic aspects of supply chain management. For practice, this further points to the importance of ensuring appropriate levels of management attention, as it was shown that the amount of management attention for a given decision was not associated with the difficulty of the decision situation (decision-making complexity) nor the importance of the decision (annual cost impact).

RQ2: How can the analytical foundation for supply chain design decisions be improved?

- Developed and tested a methodology linking literature on supply chain resilience, operational modelling and cost accounting for evaluating supply chain alternatives
- Developed a ratio indicating when strategic and tactical interactions are significant and should be explicitly considered in supply chain design decision-making. Thereby offering insight into the scoping of the evaluation of supply chain design decisions to include the consideration of significant interactions.
- Introduced a methodology for economically valuating strategic and tactical interactions and tested the ability of decision-makers to accurately evaluate such interactions, to avoid the reliance on intrinsic managerial valuations.
- Exemplified how operational data can be leveraged for predicting system behaviour when making supply chain design decisions, and thereby reducing supply chain decision-making complexity and improving decision-making effectiveness.
- Developed and tested a methodology for addressing the vulnerability of difficult to assess low-frequency high-impact disruptions when evaluating supply chain alternatives.

RQ3: How does organisational design influence the supply chain design task?

- Shown the impact of organisational complexity of the purchasing and supply management function on the effectiveness of supply chain design changes, through reduced learning and lateral relations incapable of accommodating the complex supply chain design task. Thereby contributing with insight to the organisation of the supply chain design task.

From the findings, it is clear that supply chain design decision-making can be viewed from different angles, and that these different perspectives are essential for developing a robust theoretical understanding of a complex topic like supply chain design. The thesis thus offers a comprehensive view on supply chain design decision-making reflected by Figure 7.1, depicting the research framework and the propositions distilled from addressing the three research questions. The 13 propositions offer novel insights into the understanding of the complex interactions, which influence the ability of decision-makers to make effective decisions about their supply chain design. From a practitioner's perspective, the 13 propositions, offers an understanding and guidance for the design and improvement of decision processes, decisions tools and organisational design.

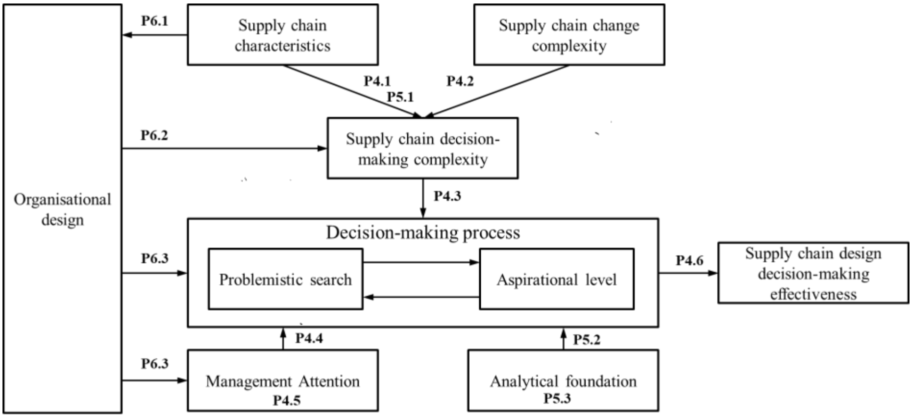

Figure 7.1: Summary of research findings and propositions

7.2. LIMITATIONS, REFLECTIONS AND FUTURE WORK

From the initiation of the research project, it has been an explicit precondition, that the research project would unfold with the specific case company, and that improving practice remained an important priority. Although I have as a researcher maintained almost full discretion in the design, planning and execution of the research work, such a precondition will inevitably influence the resulting outcome.

This influence is probably most clear when considering the broad scope of the thesis, spanning several theoretical domains, from cost accounting, production planning to behavioural research. These wide-ranging theoretical domains are all joined by the central theme of supply chain design decision-making, and the objective to improve practice in this field. In some cases the broad nature of thesis has come at the expense of the depth within a single domain, which leaves ample room for further and more focused investigation.

One relevant avenue to pursue further would be to address the reliance on a single case company. Despite the strong focus on ensuring a chain of evidence, giving substance to claimed propositions regarding supply chain design decision-making, it would be of interest to attempt to replicate the findings in both similar and dissimilar industrial settings, as well through other methodological approaches. Thereby helping to refine the understanding of the boundaries of the conclusions presented in the thesis, building on my constructed worldview, and improve the understanding of industrial, organisational and strategic contingencies, which have been controlled for with the single case research design:

As an example, it would be interesting to test if and how the strong cost focus within the case company influenced the findings. In one way, a strong cost focus could be expected to improve supply chain design decision-making through enhanced estimation ability (Wouters, Anderson, Narus, & Wynstra, 2009). On the other hand, the strong focus on cost, might reinforce biases towards specific supply chain designs with easily quantifiable benefits as it was observed in the case company, or result in the inefficient use of resources and a long time for decision-making due to a perceived need to translate all design characteristics into monetary terms. Better understanding the impact and role of cost focus on supply chain design decision-making would add more nuances to the findings presented.

Another area for further research would be to understand an organisation’s maturity into supply chain design: what are characteristics of the supply chain design capability, how does the maturity of the supply chain capability relate to performance differences, and what steps do successful firms pursue to develop their supply chain design capability?

Improving the understanding of how supply chain design is linked to firm-level performance constitute another important limitation of this research. Throughout chapter 4-6, the performance of supply chain design is assessed through a focus on the effectiveness and efficiency of supply chain decision-making regarding the procedural rationality, congruence between ex-ante prediction and ex-post realised outcomes and the resources consumed for arriving at a decision. This is a reflection of the close proximity to decision-makers and the decision-making process, which offered several novel insights into understanding how decisions unfold and constitute a basis for improving decision-making. Although decision-makers within the OEM recognised improvements in supply chain design decision-making effectiveness and efficiency, these have not been linked to firm-level performance improvements. This calls for further research, allowing the findings and propositions from this thesis to be linked to firm-level differences in supply chain performance.

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APPENDIX A: NUMERICAL EXPERIMENT FOR SUPPLY CHAIN VULNERABILITY

The following contains a numerical experiment of the Pareto frontier for alternative supply chain designs based on annual cost and different supply chain vulnerability levels reflected by the Probable Maximum Loss model introduced in Paper 6.

The numerical experiment relates to three decisions impacting supply chain vulnerability for a simple single product supply chain with annual demand of 500 units (10 units per week):

- Invest in product design changes and ensuring available resources for reducing TTR (TTR of 25 weeks. Cost of 10.000 EUR/Year for lowering TTR with 1 week.)
- Use of the second source which carries a cost through reduced volume discounts (Item cost of 10.000, 1.5% cost increase in purchase price for each 10% reduction in supplier volume)
- Use of strategic safety stock carrying a cost through inventory holding cost (Annual holding cost of 30% of the unit price).

For a supply chain design of with TTR of 15 weeks, 80% sourcing split, and 5 weeks of strategic safety stock, the PML for the simple supply chain scenario is calculated as follows:

$$0{,}8 \times 10 \times (15 - \frac{5}{0{,}8}) = 70$$

The lost production thus corresponds to 14% of annual production lost due to a disruption at the supplier. While the cost for the given supply chain design is calculated as purchase price, holding cost and investment in reducing TTR as follows:

$$\Big(1 + \big((1 - 0{,}8) \times 0{,}15\big)\Big) \times 10000 \times 500 +$$

$$5 \times 10 \times \Big(1 + \big((1 - 0{,}8) \times 0{,}15\big)\Big) \times 10000 \times 0{,}30 +$$

$$(25 - 15) \times 10.000 = 5.404.500$$

Table A.1 shows an excerpt of the results of the numerical experiment for different ranges of sourcing split, strategic stock and investment in reducing TTR.

Table A.1 Excerpt of numerical results reflecting PML and annual cost.

TTR (Wks)	Supplier split (%)	Strategic Safety stock (Wks)	TTS (Wks)	**PML (% of annual production)**	Unit Price	Holding Cost	Reducing TTR	**Annual Cost**
10	1	5	5,0	**10%**	5.000.000	150.000	150.000	5.300.000
10	0,9	5	5,6	**8%**	5.075.000	152.250	150.000	5.377.250
10	0,8	5	6,3	**6%**	5.150.000	154.500	150.000	5.454.500
10	0,7	5	7,1	**4%**	5.225.000	156.750	150.000	5.531.750
10	0,6	5	8,3	**2%**	5.300.000	159.000	150.000	5.609.000
10	0,5	5	10,0	**0%**	5.375.000	161.250	150.000	5.686.250
10	0,4	5	12,5	**0%**	5.450.000	163.500	150.000	5.763.500
10	0,3	5	16,7	**0%**	5.525.000	165.750	150.000	5.840.750
10	0,2	5	25,0	**0%**	5.600.000	168.000	150.000	5.918.000
10	0,1	5	50,0	**0%**	5.675.000	170.250	150.000	5.995.250
15	1	5	5,0	**20%**	5.000.000	150.000	100.000	5.250.000
15	0,9	5	5,6	**17%**	5.075.000	152.250	100.000	5.327.250
15	0,8	5	6,3	**14%**	5.150.000	154.500	100.000	5.404.500

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