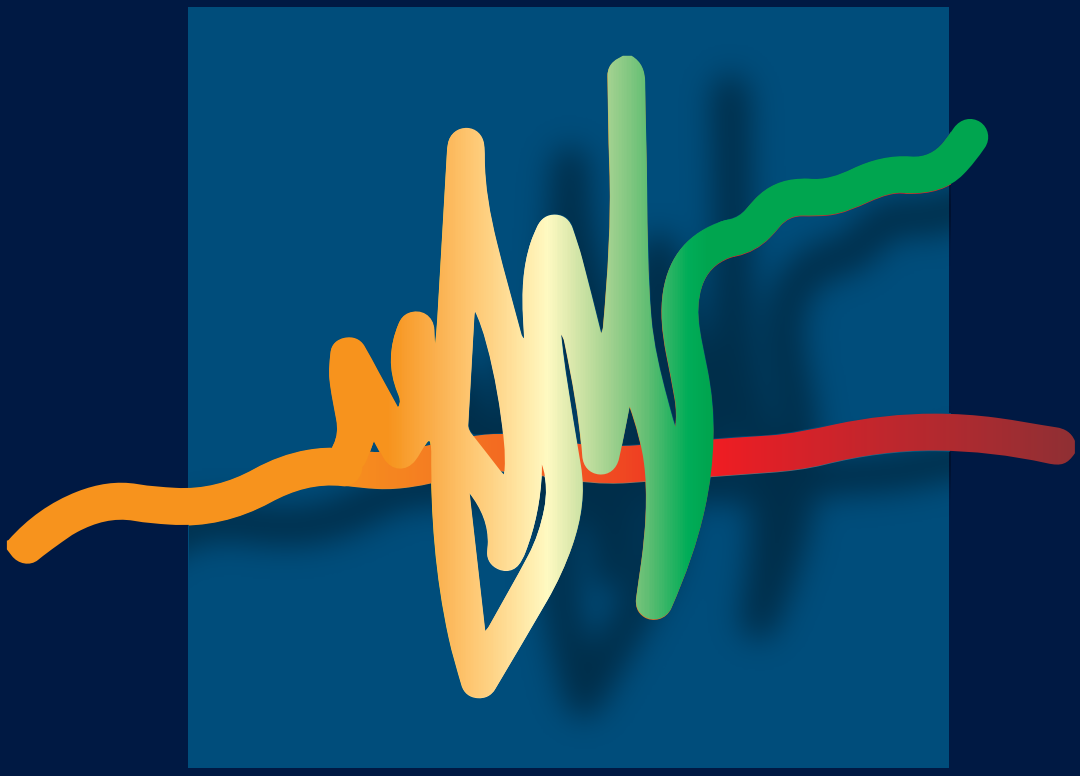
Supply Chain Disruption

The Game-changing Impact of Additive Manufacturing



Victor Verboeket

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Supply Chain Disruption:

The Game-changing Impact of Additive Manufacturing

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Summary

Supply Chain Disruption:
The Game-changing Impact of Additive Manufacturing

Additive Manufacturing (AM) – also known as 3D-printing – is one of the digital technologies associated with the 4th industrial revolution. The objective of this dissertation is to investigate the potential of AM for designing vastly improved future Supply Chains (SCs). A lack of knowledge about the effects of AM on SC design is considered a gap in the literature. To bridge this gap, this dissertation includes theoretical and empirical research. Following the introduction in Chapter 1, the main body of this dissertation consists of Chapters 2 to 5, each representing one academic article. The final Chapter 6 uses the Design Science Research (DSR) strategy, including the CIMO-logic, to integrate theoretical and empirical research. The CIMO-logic explains how interventions (I), in a certain context (C), lead to outcomes (O), through specific mechanisms (M).

The Chapter 2 article uses a systematic literature review. The results show that the main advantages of AM include the possibility to manufacture complex shapes, thus allowing for direct integration of functions into the product, or to manufacture lightweight products. Moreover, since AM does not require product-specific machines and tools, and digital files easily bypass physical boundaries, in-situ production may be allowed. These characteristics shorten and simplify SCs. Using AM in the SC may reduce cost and assets, and may improve order lead-time, but mainly for small products and short series. This article contributes to the academic knowledge base by developing 18 propositions, a conceptual model, a research agenda, and a roadmap illustrating the bottlenecks, serving as thresholds that prevent the full roll-out of AM.

The Chapter 3 article uses literature synthesis and DSR's CIMO-logic. This article contributes to the academic knowledge base by constructing six theoretical AM SC 'mechanisms' that can be used to design better performing SCs by using AM.

The Chapter 4 article combines case study research and scenario analysis to investigate a change from centralized to distributed AM production of surgical guides used in University Medical Centers. The results show that – when changing from centralized to distributed AM – the SC lead-time improves, but at significant cost increase, since investments in machines and facilities at each of the distributed locations are required.

High AM machine costs, post-processing issues, and low manufacturing speed are bottlenecks that need to be eliminated before distributed AM becomes competitive with centralized AM. This article contributes to the academic knowledge base by increasing the understanding of the relevant factors in deciding upon centralized or distributed AM production of personalized medical care products SCs.

The Chapter 5 article combines case study research and scenario analysis to investigate implementing AM in a traditional-manufacturing orthopedic shoe SC. The results show that using AM to replace traditional-manufacturing of tools and components deteriorates SC cost and lead-time performance. However, when AM of complete final products replaces traditional-manufacturing of components, lead-time significantly improves at competitive SC costs. Yet, currently, the quality of AM produced shoes is insufficient, AM production costs are too high, and traditional craftsmanship knowledge needs to be integrated into the digital design. This article contributes to the academic knowledge base by pinpointing the required conditions for AM to significantly improve SC performance in personalized medical care.

Chapter 6 uses DSR to bridge theory and practice and compares the empirical CIMO-reasoning chains derived from Chapters 4 and 5, with the theoretical mechanisms synthesized from theory in Chapter 3. This chapter contributes to the academic knowledge base by (partly) confirming the existence of four of the six theoretical mechanisms. The empirical mechanisms are valid for other non-inventory holding contexts but can be extended with the inventory-related elements. These mechanisms can be used to design significantly better performing SCs using AM.

The main conclusion of this dissertation is that AM offers great opportunities for designing significantly improved SCs, but bottlenecks, serving as thresholds prevent the full roll-out of AM. Besides, merely using AM to replace elements of the traditional SC can deteriorate SC performance. Therefore, to fully exploit AM's specific advantages, a complete redesign of the existing SC is required. The mechanisms developed in this dissertation, may serve as a tool for SC (re)design, which may ultimately lead to radical change of the existing SC structures.

Samenvatting (Dutch summary)

Disruptie van de voortbrengingsketen: De veranderingen van het spel veroorzaakt door additieve productie

Additieve productie (Additive Manufacturing, AM) – ook bekend als 3D printing – is een van de digitale technologieën die deel uitmaken van de vierde industriële revolutie. Het doel van dit proefschrift is om het potentieel dat AM levert voor het verbeteren van voortbrengingsketens (Supply Chains, SCs) te onderzoeken. In de academische literatuur wordt het gebrek aan kennis over de effecten die AM heeft op het ontwerpen van SCs als een gemis beschouwd. Om dit gemis te overbruggen, bestaat dit proefschrift uit zowel theoretisch als empirisch onderzoek. Na de introductie in hoofdstuk 1 volgt het centrale gedeelte van dit proefschrift (hoofdstukken 2 tot en met 5). Elk van deze hoofdstukken bestaat uit één academisch artikel. Het integreren van het theoretische en empirische onderzoek gebeurt in hoofdstuk 6 via de ontwerpgerichte onderzoeksstrategie (Design Science Research, DSR). DSR maakt gebruik van de CIMO-logica. Hiermee wordt beschreven hoe interventies (I), in een bepaalde context (C), leiden tot resultaten (O), veroorzaakt door specifieke mechanismen (M).

Het artikel in hoofdstuk 2 bestaat uit een systematisch literatuuronderzoek. Uit dit onderzoek blijkt dat de mogelijkheid om complexe vormen te produceren een van de belangrijkste voordelen van AM is. Dit maakt het namelijk mogelijk om lichtgewicht producten te realiseren en om functionaliteiten direct in het eindproduct te integreren. Ook een voordeel is de mogelijkheid om dichtbij de plaats van gebruik te produceren. Voor AM zijn immers geen product specifieke machines en gereedschappen nodig en digitale ontwerpen zijn gemakkelijk te verplaatsen. Al deze eigenschappen kunnen de SC korter en simpeler maken. Met name voor kleine producten en korte series kan AM zorgen voor kostenverlaging en snellere levertijden. Dit artikel verrijkt de academische kennisbasis door de ontwikkeling van 18 proposities, een conceptueel model en een onderzoeksagenda. Ook is een routekaart toegevoegd met daarin de problemen die het uitrollen van AM belemmeren en die dus moeten worden opgelost.

Het artikel in hoofdstuk 3 maakt gebruik van de literatuursynthese en de CIMO-logica. Dit artikel draagt bij aan de academische kennisbasis door het construeren van zes theoretische AM-SC-mechanismen. Deze mechanismen kunnen worden ingezet voor het ontwerpen van beter presterende ketens waarin AM wordt toegepast.

Het artikel in hoofdstuk 4 combineert casestudy-onderzoek met scenario-analyse. Het beschrijft een onderzoek naar het herontwerpen van een keten rondom chirurgische gereedschappen die gebruikt worden in universitaire medische centra. Daarbij is gekozen voor een gedistribueerde in plaats van een centrale AM-productie. Uit de resultaten blijkt dat deze verandering de levertijd verbetert. De kosten worden echter significant hoger door noodzakelijke investeringen in machines en gebouwen bij alle gedistribueerde locaties. Met andere woorden: de problemen rondom hoge machinekosten, dure nabehandeling en een lage productiesnelheid moeten worden opgelost vóórdat gedistribueerde AM interessant genoeg wordt om gecentraliseerde AM-productie te vervangen. Dit artikel verrijkt de academische kennisbasis door het expliciteren van de factoren die een rol spelen bij de beslissing voor gecentraliseerde of gedistribueerde AM-productie van gepersonaliseerde medische producten.

Het artikel in hoofdstuk 5 combineert ook een casestudyonderzoek met scenario-analyse. Dit artikel beschrijft een onderzoek waarbij AM geïmplementeerd wordt in traditionele productie van orthopedische schoenen. De resultaten van dit onderzoek: bij het gebruik van AM als vervanger van de traditionele productie van gereedschappen en componenten, nemen de kosten toe en wordt de levertijd langer. Maar wordt AM gebruikt voor productie van de volledige orthopedische schoen, dan wordt de levertijd juist veel sneller. De kosten zijn dan vergelijkbaar met de traditionele productie. Op dit moment is de kwaliteit van AM-geproduceerde orthopedische schoenen echter onvoldoende, zijn de productiekosten te hoog en moet het traditionele vakmanschap in het digitale ontwerp worden geïntegreerd. Dit artikel verrijkt de academische kennisbasis door het nauwkeurig uiteenzetten van de noodzakelijke voorwaarden voor AM bij ontwerpen van aanzienlijk beter presterende ketens van gepersonaliseerde medische producten.

Hoofdstuk 6 gebruikt DSR om een brug te slaan tussen theorie en praktijk. Dit gebeurt door de resultaten van de hoofdstukken 4 en 5 te vertalen in empirische CIMO-redeneerketens en ze te vergelijken met de theoretische mechanismen uit de literatuursynthese van hoofdstuk 3. Dit hoofdstuk verrijkt de academische kennisbasis door het (gedeeltelijk) bevestigen van de aanwezigheid van vier van de zes theoretische mechanismen. De empirische mechanismen gelden voor situaties waarin geen voorraad wordt gehouden. Echter, deze mechanismen zijn uit te breiden met elementen die relevant zijn in situaties waarin wel voorraad wordt gehouden. Daarmee zijn de mechanismen toe te passen om aanzienlijk beter presterende ketens – mét AM-productie – te ontwerpen.

De belangrijkste conclusie van dit proefschrift: AM biedt geweldige mogelijkheden voor het ontwerpen van aanzienlijk beter presterende ketens. Daarvoor moeten echter een aantal problemen worden opgelost. En wordt AM alleen gebruikt om stukjes van de keten te vervangen, dan kan dit de prestatie van de totale keten zelfs verslechteren. Met andere woorden: om de specifieke voordelen van AM optimaal te benutten, is een

volledig herontwerp van bestaande ketens noodzakelijk. De mechanismen die in deze dissertatie ontwikkeld zijn, kunnen als gereedschap dienen voor het (her)ontwerpen van de SC om zo de bestaande SC-structuren radicaal te veranderen.

Preface

Following an almost 20-year career in various international management positions, I switched to higher education in 2012 to head-up the Supply Chain Management major of the International Business School Maastricht of Zuyd University of Applied Science. This role also encompassed some academic research and I found that – although the academic world is doing great things – it is cumbersome to translate research results into businesses. Two worlds appear to exist: the business and the academic world, with – apparently – a gigantic wall in between. This intrigued me and, fortunately, I found out about the Design Science Research (DSR) strategy, which appears to be a helpful strategy to bridge theory and practice. To me - educated as an engineer – executing research aiming at designing sustainable future solutions to practical (business) problems – feels natural, hence '*bridging theory and practice*' became my motto.

In 2014, halfway my professional career, I decided to deepen my knowledge about supply chain innovation and pursue a Ph.D. degree. I obtained a Zuyd grant, which allowed me to work on my Ph.D., three days per week, from February 2016 to February 2020. Now, this era is over and here is the result.

Many people have contributed to this dissertation in various ways. Particularly important in supporting me during my daily struggle has been **Maud**, my dear wife, who had to deal with my day-to-day development. She was always the first confronted with ideas, frustrations and (few) ups. Thank you for being my partner, also in this trajectory. Also important has been **Harold Krikke**, supply chain professor, my promotor and primary constant factor in my academic development. You supported me in finding my path, provided me swiftly with feedback and gently pushed in 'my' direction. You have always respected that it was my path that I had to find myself. This exactly fitted me, you have been a great teacher, thank you, and I hope we continue our cooperation in the future. Furthermore important has been **Manon Niesten**, director of the International Business program at Zuyd. You made sure I was not overloaded with teaching activities. I am sorry for the frustrations I regularly projected on you and thank you for always being there for me. I received important academic inspiration from **Jan Holmström**, supply chain innovation professor, digital manufacturing and DSR specialist. Exactly my fields of interest, a perfect match! Your articles and conversations have inspired me. Thank you also for adopting me in your research group at Aalto University in 2017. Also important has been **Joan van Aken**, emeritus organizational science professor. You taught me about DSR, explained the differences with regular social sciences, and reflected on my

work. Thank you! The topic of my research was inspired by **Janjaap Semeijn**, supply chain strategy professor. You planted the idea of pursuing '…an attractive topic, for instance, 3D printing!…' in my mind. Thank you, you proved to be right. In addition, **Mauk Wilbers**, my retired colleague and author of the book 'Supply Chain Innovation' sparked my enthusiasm for supply chain innovation. Thank you, my friend! As my background suggests, my research is strongly connected to the business field and many field experts have been involved in this research. In particular, I like to mention the two key field experts who have participated in the empirical part of this dissertation: **Erik van de Garde**, CEO of Oceanz and **Franc van der Linden**, CEO of Hanssen Footcare. Both of you opened up your organization and shared delicate information with me. Thank you for your time, trust, help and friendship, I hope that my research supported advancing your organizations. I could not have done this without you.

Heerlen, April 17th, 2020

CHAPTER 1



Introduction

Digital technologies are rapidly changing the world we live in. This dissertation investigates how one of those digital technologies – Additive Manufacturing (AM) – can be used to design significantly improved future Supply Chain (SCs). For that purpose, this dissertation includes both theoretical as well as empirical research. While the theoretical research is not context-specific, the empirical research is limited to personalized medical products.

Holmström et al. (2016) and Waller and Fawcett (2014) consider a lack of knowledge about the effects of AM on supply chain designs as a gap in the literature. In line, the scientific contribution of this dissertation includes – by way of literature synthesis – the development of a research agenda and a conceptual model, and the construction of six 'AM SC mechanisms'. Furthermore, – by way of empirical research in personalized medical products SCs – this dissertation contributes to science by understanding the relevant factors for deciding for centralized or distributed AM production, and about deciding for the implementation of AM in traditional-manufacturing. Finally – through the development of 'CIMO reasoning chains' based on the empirical work – (partial) evidence for four of the six theoretical 'AM SC mechanisms' is found, thus creating new knowledge, which is transferable to other contexts. The mentioned CIMO-logic is used throughout this dissertation and explains how interventions (I), in a certain context (C), lead to outcomes (O), through specific mechanisms (M).

Next, Section 1.1 discusses the contemporary developments in supply chain design. Section 1.2 introduces the main concepts used in this dissertation. Section 1.3 explains the main objective and research questions. Section 1.4 justifies the overall methodology. Section 1.5 explains how the empirical research is selected. Section 1.6 concludes this introduction by explaining the structure of this dissertation.

1.1 Contemporary SC design developments

An SC is the flow of materials, information and money from the source to the consumer and back (Mentzer et al., 2001). Designing an SC involves choices concerning assortment, location and size of the production and warehousing facilities, the IT systems, the transportation modalities, and the people working in the chain (Chopra and Meindl, 2013). Historically, SCs have undergone both **incremental** and **disruptive changes** following the technological and societal trends at any point in time. Incremental changes are relatively small, for instance through quality improvement or lean techniques (Holweg, 2007), contrary to disruptive changes – or **game-changers** – where the roles of the stakeholders in the SC significantly alter (Fawcett and Waller, 2014). These changes date back to ancient history but were accelerated during the industrial revolutions. The first industrial revolution was triggered by the invention of the steam engine in the 18th century. The second industrial revolution was set off

by the invention of electricity, and the third industrial revolution was caused by the invention of information and communication technology in the 20th century. According to the World Economic Forum, society is currently on the verge of 'the Fourth Industrial Revolution', where advanced technologies will dramatically change society (Swab, 2017). Examples of these technologies include mobile supercomputers, artificial intelligence, blockchain technology, autonomous vehicles and AM – the digital manufacturing technology discussed in this dissertation.

To illustrate the effects of technological advances on supply chains, let us return to the early 20th century. Henri Ford used to say that you could order any color of T-Ford, as long as it was black. This is in sharp contrast to current practice, where mass-customization is often the standard. In the late 20th century, globalization has moved manufacturing from taking place near the point of consumption to taking place in low labor-cost countries. This has reshaped jobs, factories, transportation modalities and inventories in different places of the world, where concurrently new markets emerged in developing economies. Besides, the rise of internet shopping has disrupted traditional-shopping during the last two decades. Physical shops went digital, leaving the inner cities empty while large distribution centers were built near motorways. Transportation modalities have changed from trucks to vans. Besides, the nature of people's jobs has changed from, for instance, shop employees to warehouse associates. A very recent trend is the appearance of digital platforms, where, using smart internet supported tools, assets can be shared between multiple users. Digital, intangible products replace physical, tangible products. Examples include the classic music and video industry where consumers would buy a vinyl record or videotape while new business models (e.g. Spotify and Netflix) provide streaming services through digital platforms. Other platforms include sharing distribution (truck) capacity; first movers include uberfreight.com and pamyra.de. Hence, physical SCs more and more turn into **digital supply chains** (Büyüközkan and Göçer, 2018). The increased attention given to sustainability has led to the Sustainable Supply Chain Design where the triple bottom line (people-profit and planet) is well-balanced (Bals and Tate, 2018).

Heading forward, many unknown, partly contradictive and potentially disruptive changes are upcoming, and SC designs will require continuous redesign to adapt to contemporary developments. On the other hand, Western societies are in comfortable positions and they experience little need to actively prepare for the upcoming change. Nevertheless – considering the law of the inhibiting lead – business models may well be disrupted when failing at looking ahead. This dissertation develops methods for improving SC performance in the unknown future by predicting the effects of AM and pinpointing the bottlenecks, serving as thresholds that prevent these changes from happening.

1.2 Main concepts

Supply Chain Management (SCM) aims at optimizing customer value and improving the competitive advantage by – for instance – lowering costs, increasing responsiveness and managing demand variation (Mentzer et al., 2001). SCM is rooted in Logistics and Operations Management, and has diffuse borders and overlaps with many other fields, for instance with marketing, finance, human resource management, environmental sciences, information technology, and facility management. To standardize SCM terminology and enable benchmarking the **SCOR model** (APICS, 2018) has been developed. Throughout this dissertation, the SCOR categories Plan, Source, Make, Deliver, Return and Enable are used for structure and definitions. The **Customer Order Decoupling Point (CODP)** – also called the Order Penetration Point (OPP) is the point in the SC where the order becomes customer-specific (Olhager, 2003, Olhager, 2010). Due to increasing competition and consumer emancipation, companies aim at reducing (inventory) cost, while at the same time meeting or exceeding the increased customer expectations. Therefore, and in line with the (mass) customization and personalization trends, SC designs aim at 'postponing' the CODP from Make-to-Stock **(MtS)**, to Make-to-Order **(MtO)** or Engineer-to-Order **(EtO)** (Hsuan Mikkola and Skjøtt-Larsen, 2004, van Hoek, 2001). Digitization of SCs may eliminate SC steps, a concept called '**SC disintermediation**' (Mills and Camek, 2004), where SC steps are removed by changing from traditional commerce to e-commerce. Every SC produces 'results' – also known as outputs or **outcomes** – which, according to Melnyk et al. (2010) and APICS (2018), are a mix of cost, responsiveness, assets, reliability, flexibility, resilience, security, sustainability, innovation. Throughout this dissertation, mainly the traditional and measurable outcomes **cost** and **lead-time** are used.

Additive manufacturing is a digital manufacturing technique also known as **3D-printing** which is used for different applications, such as Rapid Prototyping (RP), Rapid Tooling (RT) and Rapid Manufacturing (RM). The difference with **(traditional) subtractive-manufacturing** is that in subtractive-manufacturing pieces are removed from a solid piece (for instance through milling, sawing or drilling), whilst in AM material is added layer by layer (ISO/ASTM, 2015). AM was invented in the early nineteen eighties and first used for prototyping (RP) applications, mainly using plastics. As the technology matured, more materials became printable, for instance, heat resistant polymers, which allowed extending AM to tooling (RT) applications. Rayna and Striukova (2016) consider RP and RT applications mature, contrary to the final product (RM) applications. However, Maresch and Gartner (2018) mention various RM applications in different industries. For instance for the manufacturing of (very) low demand spare parts, personalized consumer products (e.g. jewelry), and personalized medical care products, for instance for implants, surgical tools and hearing aids (Emelogu et al., 2016, Giannatsis and Dedoussis, 2009, Huang et al., 2013). This dissertation is also about **personalized medical care products**: surgical guides in Chapter 4 and orthopedic shoes in Chapter 5.

AM offers certain advantages over subtractive-manufacturing. For instance, its additive nature allows for the creation of shapes impossible to create using subtractive techniques. Also, for manufacturing only a machine, one kind of raw material and a digital file are required. Moreover, since digital files and raw materials (relatively) easily bypass physical boundaries, on-location (in-situ) manufacturing becomes possible. This makes AM particularly suitable for manufacturing in difficult-to-reach locations, for instance, polar areas, extraterrestrial areas and war zones (De la Torre et al., 2016, Holmström et al., 2017, Ryan et al., 2017). Therefore, the positioning of AM in the SC (the SC configuration) needs to be decided upon. The theory distinguishes central, distributed and mobile configurations. **Centralized AM production** (Mellor et al., 2014, Rylands et al., 2016) can be combined with distributed scanning (Rogers et al., 2016). Moreover, **distributed AM production** (Bogers et al., 2016, Mohr and Khan, 2015, Moore et al., 2016) – also called '**in-situ** AM production' – can be combined with centralized coordination (Eyers and Potter, 2015), or centralized design (Oettmeier and Hofmann, 2016), and requires sufficient local demand (Chekurov and Salmi, 2017). Mobile AM is suitable for in-transit manufacturing and is easy to reposition close to changing demand (Kothman and Faber, 2016, Ryan et al., 2017). In this dissertation, the Chapter 4 case investigates the centralized as opposed to distributed AM production in an SC. Another advantage of AM is the possibility to **directly integrate functions** in the product design. The literature mentions the direct integration of thermodynamic functions – for instance, cooling channels – in the construction industry (Kothman and Faber, 2016). Also mentioned are product designs with assembled parts inside, thus reducing the assembly efforts (Atzeni and Salmi, 2012, Wagner and Walton, 2016, Yang and Zhao, 2015). In line, in the Chapter 5 case, also functions are directly integrated into the design of the final orthopedic shoe.

1.3 Main objective and overarching research questions

Popular literature often describes AM as disruptive for SCs and business models (Accenture, 2014, Cohen et al., 2014), but the academic literature appears to have a more subtle view. For instance, according to Holmström et al. (2017), AM is currently immature and only able to support traditional manufacturing. On the other hand, Steenhuis and Pretorius (2017) mention that AM may cause both small as well as big changes to existing business models, while Fawcett and Waller (2014) mention potential big changes when, for instance, local AM production replaces centralized mass-manufacturing. In line with this academic discussion **the main objective of this dissertation is to investigate the potential of AM for significant SC performance improvement.**

The major SC performance improvements appear to be related to cost and lead-time. Besides customization at no extra cost (Holmström et al., 2017, Weller et al., 2015), AM

can reduce costs, which includes the reduction of cost of raw materials and finished goods inventories, as well as reductions in production, assembly and transportation costs (Atzeni and Salmi, 2012, Ford and Despeisse, 2016, Mohr and Khan, 2015). However, AM may be more expensive than traditional-manufacturing for larger series and bigger products (Berman, 2012, Thiesse et al., 2015, Walter et al., 2004). Lead-time improvements may also be reached, but mainly for products with complex geometries and for small series (Giannatsis and Dedoussis, 2009, Petrick and Simpson, 2013, Ryan et al., 2017). Therefore the first overarching research question is:

RQ1. What are the effects of AM on SC cost and lead-time performance?

Although AM offers many advantages over subtractive-manufacturing, still many material, processing, regulatory and people related **bottlenecks** serve as **thresholds** and prevent the full roll-out of AM (Durach et al., 2017, Dwivedi et al., 2017). Hence the second overarching research question is:

RQ2. Which bottlenecks, serving as thresholds, have to be eliminated before AM can radically improve SC performance?

In Section 2.4 a (theoretical) roadmap explains how AM develops towards maturity once these bottlenecks are eliminated. This roadmap is supported by the empirical studies, which show that, currently, stable and repeatable product quality, high AM production costs, post-processing issues, low manufacturing speed, and insufficient knowledge about designing for AM, are bottlenecks that serve as thresholds which need to be eliminated before AM can have the necessary (disruptive) effects, that leads to significant SC performance improvement.

The additive nature requires no product specific machines and tools and allows for building differently shaped products in the same production batch, as opposed to subtractive-manufacturing where economies of scale (depreciation of expensive machines and tools) are reached only through large batch manufacturing. Consequently, AM induces other 'mechanisms' than traditional-manufacturing, where an AM SC mechanism is defined as the link between the SC design elements (including AM) with the SC outcomes in a given context. Accordingly, the third overarching research question is:

RQ3. How are AM interventions turned into SC performance outcomes, i.e. which SC mechanisms are induced by AM?

In Chapter 3, six AM SC specific mechanisms are synthesized from theory. Moreover, empirical research (in Chapters 4 and 5) is used to confirm the existence of four of these six mechanisms. Chapter 6 discusses this and also reflects on the overarching research questions.

1.4 Overall methodological strategy: Design Science Research

This dissertation uses Design Science Research (DSR) (van Aken et al., 2016) as an overall methodological approach. Studying new solutions where the theoretical concepts are not yet well defined, and the problem context and solutions are still unstructured, is cumbersome from a methodology perspective. As a solution to this hurdle, Handfield and Melnyk (1998) suggest using an exploratory and descriptive approach in the operations management field while the theory is still developing. DSR is utilized by researchers in the field of operations management – as well as the other management fields – to explore and explain novel practices and solutions (Holmström et al., 2009). DSR is considered an overarching research strategy, and therefore any research method (e.g. case study or scenario analysis) can be utilized in its process. Kaipia et al. (2017) advocate using case study research for data collection to be used as input for designing artifacts in a DSR project. In line, in Chapters 4 and 5, case study research is used for data gathering and DSR for designing and evaluating future scenarios.

DSR methodology utilizes the so-called 'CIMO-logic' in design propositions and provides the basis for theory development in the management field. CIMO-logic determines the Context (C) in which Interventions (I) lead to the Outcomes (O) through specific Mechanisms (M). In other words, based on the empirical data, design research articulates how – in a specific situation – an intervention would lead to the expected results. The mean-ends proposition is a similar logic that can be used for design proposition development; it serves as a bridge between theory and practice and has been employed as a method in many academic contributions (Holmström et al., 2009). Subsequently, the CIMO-logic has been applied in several ways throughout this dissertation. Chapter 3 uses the CIMO-logic to synthesize literature and construct six AM SC specific mechanisms. Chapter 4 applies the CIMO terminology: the context (C) is the patient-specific medical care SC for surgical guides provided to University Medical Centers using centralized, outsourced AM; the intervention (I) is the alternative SC design scenario using distributed AM; the outcomes (O) are the SC outcomes measured in SC cost and SC lead-time. Chapter 5 also uses the CIMO terminology: the context (C) is the patient-specific medical care SC for orthopedic shoes using traditional-manufacturing; the intervention (I) is a scenario where AM – in varying degrees – replaces the traditionally manufactured of components and tools, the outcomes (O) are the SC outcomes measured in SC cost and SC lead-time. Figure 1.1 explains the overall conceptual model of this dissertation in CIMO terms.

A three-step approach to developing a design proposition involves (1) exploration to frame the problem, (2) abduction of existing solution elements, and (3) field testing and evaluation (Aliseda-Llera, 1997, Holmström et al., 2009, Magnani, 2011). In the exploration step, possible interventions – includes implementing a new technology or a novel practice – are considered, bearing in mind the intended context and purpose.

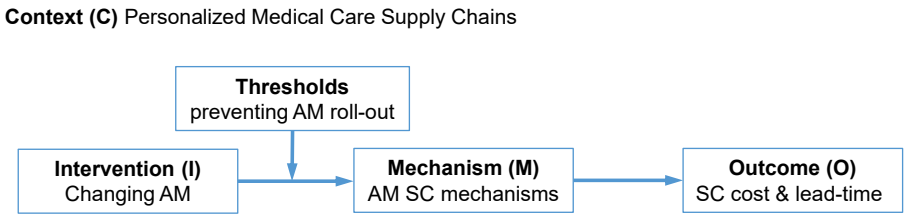


Figure 1.1: Conceptual model including CIMO-logic.

The outcome of the exploration phase is to identify a field problem and a suitable context for further development and small-scale experimentation. In the second step – abduction – new solution designs are created through the combination and modification of existing solutions from other fields of science. In the final step – field-testing – the researcher tries to solve the problem in the context that was framed in the first step. If an intervention can become more interesting through modifications, the first step needs to be revisited. Finally, a process of evaluation and explanation utilizes the findings of previous steps to define the CIMO-logic and clarify how – and through what mechanism – the intervention led to the outcomes. The empirical chapters (4 and 5) follow these three steps, although the field-testing is limited to developing, calculating and evaluating potential future scenarios. In chapter 6 – based on the empirical Chapters 4 and 5 – the CIMO-reasoning chains are developed and compared to the AM SC mechanisms developed from theory in Chapter 3. Figure 1.2 explains the overall DSR strategy of this dissertation.

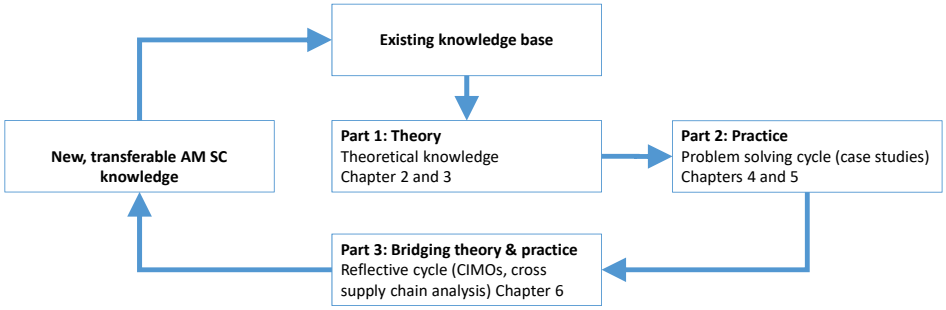


Figure 1.2: Overall DSR strategy of this dissertation (adapted from van Aken and Andriessen (2011)).

1.5 Empirical research on AM contribution to SC performance

Besides the theoretical analyses based on literature, empirical research has been executed to discover evidence for the theoretical insights that aim at designing better performing SC by using AM. In the empirical component of this dissertation, two case studies into personalized medical products SCs have been performed. Evaluating medical products SCs is relevant since – besides the rising expectation about the quality of care – healthcare costs are high and continue to rise. In the EU, healthcare costs have risen from 8.8% of GDP in 2008 to 9.6% of GDP in 2017 (OECD/EU, 2018). More specifically, healthcare costs in the Netherlands are expected to double from 87 billion Euros in 2015 to 174 billion Euros in 2040 (RIVM, 2018). The main causes are an aging population and technological advances – for instance, new medication and equipment. Although advancing technology increases healthcare costs, it also may offer an opportunity to reduce costs. This dissertation anticipates these developments by predicting the effects of AM on SC (cost and lead-time) performance and developing methods to manage this.

As mentioned, this dissertation uses case study research and Yin (2014) considers generalizing (or transferring) the results of case study research to other contexts a challenge. To improve analytical generalizability (or external validity) the cases should be common, but not too common and also polar for explanatory reasons, but not too polar for comparability reasons (Meredith, 1998). Accordingly, the two case studies were selected by evaluating the key common and polar characteristics. Moreover, the selected cases aim at providing evidence for the theoretical AM SC mechanisms, as developed in Chapter 3. Since mechanisms are context and intervention dependent, it has been decided to keep the context comparable and to vary the intervention, see Table 1.1. The cases will be explained in detail in the respective Chapters 4 and 5.

Table 1.1: Common and polar characteristics of the cases

	Chapter 4 surgical guides	Chapter 5 orthopedic shoes
Common characteristics	• Personalized medical care products SC context; • Netherlands context	• Personalized medical care products SC context; • Netherlands context
Polar characteristics	• Surgical guides supplied to University Medical Center (UMC) • Current SC uses AM • Intervention: from central AM to distributed AM	• Orthopedic shoe SC supplied to patients • Current SC uses traditional-manufacturing • Intervention: AM replaces traditional-manufacturing

1.6 Dissertation structure

Following this introductory chapter, the main body of this dissertation consists of Chapters 2 to 5, each representing one academic article. Chapters 2 and 3 are published and theoretical, while Chapters 4 and 5 are empirical and in the process of being published. The final Chapter 6 uses the DSR strategy to integrate theoretical and empirical research.

Part 1: Theory

Chapter 2 consists of the article *'The disruptive impact of additive manufacturing on supply chains: A literature review, conceptual framework and research agenda'.* This article is authored by Victor Verboeket and Harold Krikke and is published in the international (peer-reviewed) journal 'Computers in Industry' (Impact Factor 4.8) in August 2019. This article uses a systematic literature review and analyzes 67 (peer-reviewed) articles to determine the impact of AM on SCs. This article contributes to the academic knowledge base by developing 18 propositions, a conceptual model, a research agenda, and a roadmap illustrating the bottlenecks, which serve as thresholds that need to be resolved before AM can significantly improve SC performance.

Chapter 3 consists of the article *'Additive Manufacturing: A game-changer in supply chain design'.* This article is also authored by Victor Verboeket and Harold Krikke and is published in the international open access and peer-reviewed journal 'Logistics' in April 2019. This article contributes to the academic knowledge base by – through literature synthesis – constructing six AM SC mechanisms that can be used in SC design to achieve SC outcomes.

Part 2: Practice

Chapter 4 consists of the article *'Additive Manufacturing in Patient-Specific Medical Care: A Case Study on Central versus Distributed Supply Chain Configurations'.* This article is a co-creation with Aalto University and is authored by Victor Verboeket, Siavash Khajavi, Harold Krikke, Mika Salmi and Jan Holmström. This article has been submitted to and rejected by (with the option to resubmit) the international (peer-reviewed) journal 'Computers in Industry'. The article combines case study research and scenario analysis to investigate a change from centralized to distributed AM production of surgical guides used in University Medical Centers (UMCs). This article contributes to the academic knowledge base by increasing the understanding of the relevant factors in deciding upon centralized or distributed AM production of patient-specific medical care products SCs. It also guides decision-makers at University Medical Centers, AM service providers, and equipment manufacturers.

Chapter 5 consists of the article *'Pinpointing Supply Chain Disruption: a case study on introducing additive manufacturing in traditional orthopedic shoe manufacturing'.* This article is authored by Victor Verboeket, Harold Krikke, and Mika Salmi. This article was submitted to and rejected by (with the request to resubmit) the international (peer-reviewed) journal 'Journal of Operations Management'. The Chapter 5 article combines case study research and scenario analysis to investigate implementing AM in a traditional-manufacturing orthopedic shoe SC. This article contributes to the academic knowledge base by pinpointing the required conditions for the significant performance improvement of personalized medical care supply chains by introducing AM. This article also provides guidance for health care policymakers, providers and insurers for reorganizing their business model and SC.

Part 3: Bridging theory and practice

Chapter 6 concludes this dissertation, reflects on the key research questions, provides directions for future research, and uses DSR to bridge theory and practice by comparing the empirical 'CIMO-reasoning chains' (derived from Chapters 4 and 5) with the theoretical mechanisms synthesized from theory (in Chapter 3). This chapter contributes to the academic knowledge base by (partly) confirming the existence of four of the six theoretical AM SC mechanisms. These mechanisms can be used to design significantly better performing SCs by applying AM.

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PART 1
THEORY

"Building on the shoulders
of giants"

Isaac Newton

CHAPTER 2



A literature study, conceptual framework and research agenda

This chapter is published as VERBOEKET, V. & KRIKKE, H. 2019. The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. *Computers in Industry,* 111, 91-107.

Abstract

Additive Manufacturing (AM) is one of the advanced computer technologies that digitizes supply chains (SCs). This article presents a structured literature review on the impact of AM on SC design based on 67 peer-reviewed articles. We address the business settings in which AM operates, AM SC design choices, and AM SC performance outputs. We use the SCOR model to structure this article.

Our results show that while AM is currently used for many applications it is mainly used for small, low demand and geometrically complex products. SC design involves making choices related to SC configurations, supplier relationships, AM production, installation of a return channel, IT system requirements and human resources. The main SC performance outputs influenced by AM are (reduced) SC cost and (improved) SC responsiveness. Many bottlenecks prevent AM being used to its full potential.

This article contributes to the AM SC design knowledge base by developing a conceptual framework, including 18 propositions, and a research agenda identifying relevant AM SC design research themes. Moreover, a roadmap is presented describing the steps to a full roll-out of AM for manufacturing purposes, in which bottlenecks (serving as thresholds) need to be eliminated in order to trigger a series of disrupting SC effects. We expect that AM will eventually lead to SC disruption, and has the potential to largely replace conventional manufacturing for mainstream products.

2.1 Introduction

3D-printing, rapid-prototyping, rapid-tooling and rapid-manufacturing are all digital manufacturing techniques commonly known as Additive Manufacturing (AM) (ISO/ASTM, 2015). AM is considered to be one of the key developments in the 4th industrial revolution (Swab, 2017), and one that strongly affects supply chains. A supply chain (SC) can be described as a set of actors in several businesses directly involved in the stream of materials, money and data from the origin to the end user, and vice versa, with the purpose of creating value for the customer (adapted from Mentzer et al., 2001). Our society is digitizing and, as a result of this, information and communication technology is becoming increasingly important in the SC management field. Büyüközkan and Göçer (2018) describe a digital SC as a 'value driven, smart process that generates business using new, analytical and technological processes including the internet of things, sensors, cloud computing, robotization and automation'. A SC design should support the customer value creation process by optimizing choices related to systems, participants, the positioning and size of manufacturing and warehousing locations, and transportation modalities. This SC design should provide the desired outcomes, for instance good quality products and services at low cost, and be capable of adapting quickly to changing supply and demand (Chopra and Meindl, 2013).

AM is a collection of different techniques and possesses different characteristics to Conventional Manufacturing (CM). Whereas in CM, pieces of material are removed from a solid piece, in AM, basic materials are added layer-by-layer. AM was developed in the 1980s. The first applications in the 1990s were rapid-prototyping and rapid-tooling, applications which are by now considered to be 'mature'. This is in contrast to both direct digital manufacturing AM applications for production of final parts (started in the 2000s) and home fabrication by consumers (only recently started), which are not yet considered to be mature (Rayna and Striukova, 2016). Availability of a digital design, which can be co-created using a customer platform, is a prerequisite of AM. AM has several advantages over CM. Shapes that are traditionally impossible, difficult, or expensive to produce with CM become possible using AM. Furthermore, the direct-integration of functions in a product becomes possible, and the manufacturing of lightweight products is enabled. Note that products can be manufactured from a single basic material (often powder), and, due to process efficiency, less basic material is needed. As manufacturing can be carried out using one process and one machine, no unique equipment is necessary, and therefore fewer assets, for example specialized machines and factories, are required. Moreover, data files travel more easily than tangible products. These factors facilitate manufacturing near the point of use. This leads to a change in transportation requirements, meaning that certain SC elements may become redundant, and relationships in the chain will therefore change. In line with this, the need for stock keeping may decline, and cheaper, personalized products

may now be produced. In relation to medical products, this will in turn improve the standard of general healthcare (Emelogu et al., 2016, Oettmeier and Hofmann, 2016). Manufacturing (of spare parts) in hard to reach places – for example, polar areas, space stations or disaster areas – can improve equipment up-time (De la Torre et al., 2016, Meisel et al., 2016). However, it is worth noting that although AM is promising for manufacturing purposes, there are also disadvantages to this production method, and bottlenecks do exist. For example, materials for printing may be scarce, and machine and material prices can be high. Product guarantee and (digital) ownership can become unclear, data transfer can be corrupted, and costs for large series may be high (Durach et al., 2017, Dwivedi et al., 2017). Moreover, although the complete SC consumes less energy due to a reduced need for materials and transportation, the manufacturing and material preparation processes consume considerably more energy (Li et al., 2017).

Popular literature often portrays AM as being disruptive to businesses and their supply chains (Accenture, 2014, Cohen et al., 2014) while peer reviewed academic literature presents a more nuanced view. For instance, Steenhuis and Pretorius (2017) note that the use of AM can result in major as well as minor changes to existing businesses. Fawcett and Waller (2014) focus on the major changes that occur when AM products are produced at or near the point of consumption instead of in centralized factories. However, Holmström et al. (2017) point out that because AM technology is not yet fully developed, it is (currently) only suitable for supporting CM. In order to contribute to this academic discussion, this article investigates the impact of AM on SC design and on SC performance outputs. Both Waller and Fawcett (2014) and Holmström et al. (2016) recognize the need for further research in this area and call for more work to address the current gap in the literature.

This structured literature review contributes to the field by developing a conceptual framework, consisting of propositions and an Input-Process-Output model describing the AM and SC design relationships. It would appear that mature AM is likely to have disruptive effects on SCs, once bottlenecks serving as thresholds are eliminated. Therefore, we propose an academic research agenda outlining the disruptive effects of AM on SCs, and provide a roadmap, which paves the way for the optimal introduction of matured AM in SC designs.

2.2 Methodology

A structured literature review serves to provide a solid theoretical foundation from which further research can emerge. Tranfield et al. (2003), and Rousseau et al. (2008), have suggested using a five step approach. First, research questions are formulated; second, a search is conducted for the relevant articles; third, the articles are chosen

and assessed; fourth, the results are analyzed and integrated and fifth, the information is applied. The next sections elaborate on these steps.

2.2.1 Research questions

The main objective of this study was to increase knowledge on the disruptive impact AM has on supply chain designs. This main objective was broken down into six research questions (RQs). RQ 1 through RQ 3 were guided by the Input – Process (transformation) – Output (IPO) 'cause and effect' model (Zwikael and Smyrk, 2012), see Figure 2.1. This led to the development of the conceptual framework, including propositions describing the AM – SC design relationship (RQ4) and the research agenda (RQ5) designed to test the propositions and provide a roadmap (RQ6) to the roll-out of AM (once the hurdles preventing dispersion of AM are resolved).

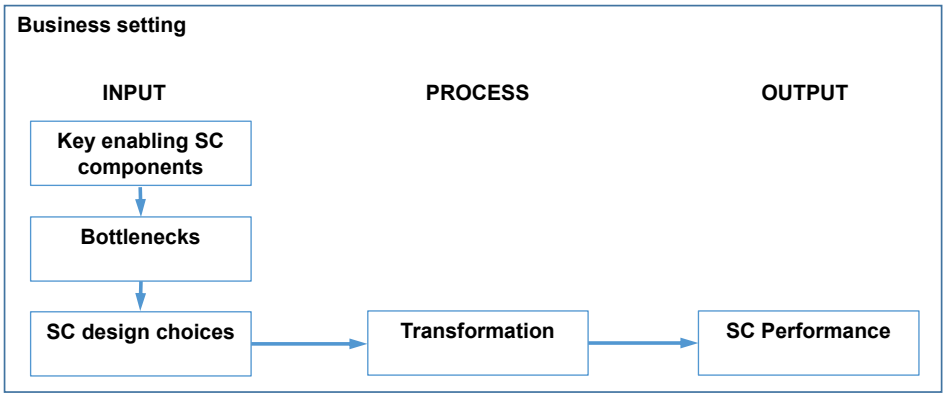


Figure 2.1: IPO Relationships (adapted from Zwikael and Smyrk (2012)).

RQ1. In which SC business settings does AM thrive?
RQ2. How does AM affect SC design choices and which bottlenecks prevent AM from being used to its full potential?
RQ3. How can AM influence SC performance outcomes?
RQ4. How can cause and effect relationships between AM SC design and SC performance outcomes, possibly constrained by bottlenecks, be modelled in a conceptual framework?
RQ5. What does the SC design research agenda to further boost SC performance look like?
RQ6. What does the roadmap for the roll-out of AM for manufacturing purposes (once the bottlenecks that currently prevent dispersion of AM are eliminated) look like?

2.2.2 Literature search

In order to capture the right articles, the following search terms were specified: 'supply chain' and 'additive manufacturing'. In addition, their interchangeable terms were identified and connected by 'AND' and 'OR' connectors. This resulted in the following formula:

(('supply chain' OR 'supply network' OR 'logistic' OR 'value chain' OR 'network design') AND ('additive manufacturing' OR '3d printing' OR '3 dimensional printing' OR 'rapid manufacturing' OR 'rapid prototyping' OR 'rapid casting' OR 'rapid tooling' OR 'stereo lithography' OR 'digital manufacturing' OR 'solid free-form' OR 'layer manufacturing' OR 'material deposit manufacturing' OR 'material addition manufacturing' OR 'additive layer manufacturing')).

The university library software was used and provided access to the major online information sources and search machines such as Science Direct (Elsevier), Web of Science, Google Scholar and Directory of Open Access Journals.

2.2.3 Choosing and assessing the articles

Using the search terms specified above, peer-reviewed articles were collected in the online databases. The literature search found 503 articles and papers all published before January 2018. Based on an examination of the abstracts, 456 articles were rejected on the grounds that they did not include SC design elements, SC performance outputs or bottlenecks according to the coding scheme explained in section 2.4. The excluded articles primarily discussed digital or SC modelling, materials or AM techniques. The reason for exclusion was registered in a database. The remaining 47 articles were studied in their entirety. An additional 20 articles were found via references in the studied articles that were not yet included in our research (snowballing) and as a result of suggestions made by peers. The literature study described below is based on these 67 articles – published in 29 different journals and covering a wide range of topics, thus reducing the likelihood that any important information was missed. Twenty-nine articles were sourced from journals covering manufacturing, production and technology; 13 from operations management, logistics and SC journals; five from information systems journals; five from business and economics journals. The remaining 15 articles were published in journals covering social, ethics, ecology, energy, materials and engineering. The required SC information in the articles was frequently concealed, or in some way unclear, reflecting the complicated problems often observed in organizations (Denyer et al., 2008). Although all 67 articles were peer-reviewed, only a minority of these articles were based on empirical evidence. Nevertheless, the others were kept in the set because their described experience and know-how provides helpful information.

2.2.4 Analyzing and integrating the results

The business setting, input, output, and bottleneck elements found in the 67 articles were coded according to the coding scheme detailed below, and entered in a spreadsheet for analysis.

- The business setting of the SC was analyzed in terms of product life cycle (Levitt, 1965, Sundin and Bras, 2005), industry and product type (NAICS, 2017), sales channel (Gummesson et al., 2009), and demand characteristics (Mangiaracina et al., 2015).
- The (input) SC design choices were analyzed according to the definition of Chopra and Meindl (2013) and combined with the following SCOR elements: plan, source, make, deliver, return and enable (APICS, 2018, Stewart, 1997). 'Plan' refers to SC configuration choices, the Order Penetration Point (OPP) (Olhager, 2003) and the assortment choices; 'Source' refers to the basic material and partner choices; 'Make' refers to the choices related to AM within the production facilities; 'Deliver' refers to the choices related to warehousing and the transportation modes; 'Return' includes decisions related to closed loop processes (Krikke et al., 2013); 'Enable' refers to decisions related to IT systems and to human resources. The bottlenecks preventing AM implementation from reaching its full potential were analyzed in terms of products, materials, processes, regulations, and other bottlenecks (Durach et al., 2017, Dwivedi et al., 2017).
- The SC performance outputs were analyzed according to Fronia et al. (2008), who define the SCOR related SC performance outputs as: cost, assets, responsiveness, reliability, and flexibility. In line with this, Melnyk et al. (2010) propose that the SC performance output can vary in terms of cost, responsiveness, resilience, security, sustainability and innovation. In addition to the outputs the SC should produce (desired outputs), undesired outputs (Holmström et al., 2009) were also identified.

2.2.5 Applying the information

The coded information in the spreadsheet was used to analyze the relationships between the SC design (i.e. cause or input) and SC performance outputs (i.e. effect or output) and to develop a conceptual framework by formulating propositions and proposing a conceptual input-process-output model in which influential bottlenecks are also specified. Subsequently, we developed a research agenda, highlighting the SC research areas related to proposition testing and providing a time-phased roadmap to the future full roll-out of AM, in which bottlenecks are eliminated step-by-step. The results are explained in Section 2.3.

2.3 Results and Discussion

This section relates to the first contribution of this article by developing a conceptual framework (Section 2.3.4) using the narrative results of the structured literature review (Sections 2.3.1 to 2.3.3). The relevant references are listed in a table at the end of each section.

2.3.1 AM in business settings

This section relates to RQ1 and explains the business settings in which AM thrives, according to the AM SC literature.

Originating as rapid prototyping, AM is often used in the development phase of the product lifecycle. This application is mainly found in the manufacturing industry for parts and assemblies, in the aeronautics industry for consumer products, and in the healthcare industry for medical devices. AM is also used for rapid tooling, e.g. inlays for mass-production molds. According to Rayna and Striukova (2016), the use of AM for the production of final products (rapid manufacturing) is developing towards maturity. For example, AM is used in the healthcare industry to make customized medical devices (stents, hearing aids) and surgical tools, and in the manufacturing industry for lightweight or geometrically complex industrial parts and assemblies (e.g. filters). AM's ability to manufacture complex shapes (shape freedom) also allows for the production of lightweight parts and assemblies in aeronautics, and for the manufacturing of highly customized products, for example the personalized construction of houses. In the retail industry, it allows for the personalization of consumer products, for example the design and production of personalized food such as chocolate, due to the fact that AM allows the design and production phases to concur. Applications in the end-of-life phase of the product life cycle include spare parts production, particularly in the aeronautics industry. Walter et al. (2004) mention that AM, from a cost perspective, is particularly suitable for small products. Besides the manufacturing of highly customized products, AM also allows for the manufacturing of products in short-supply. AM is also used for (very) low-demand or single unit demand products. Sirichakwal and Conner (2016) explain this by pointing out the diminishing cost advantage of AM when demand increases. Typical low-demand industrial applications include spare parts, tools and parts and assemblies. Low-demand consumer products can include customized products e.g. lamps. These products can have big spikes and drops in demand. Maresch and Gartner (2018) analyze online magazines in Germany and mention, in addition to those outlined in the AM SC literature, AM applications for art, hobby, fashion, jewelry and education. A full list of references can be found in Table 2.1.

Table 2.1: Business setting literature

Topic	References
AM of final products heading towards maturity	Rayna and Striukova (2016)
Rapid prototyping applications	Berman (2012), Fawcett and Waller (2014), Holmström et al. (2017), Raja et al. (2006), Thiesse et al. (2015), Waller and Fawcett (2014)
Manufacturing industry, parts and assemblies	Chua et al. (2005), Vinodh et al. (2010)
Aeronautics industry	Wagner and Walton (2016)
Consumer products	Chin (1998)
Healthcare industry, medical devices	Giannatsis and Dedoussis (2009), He et al. (2006)
Rapid tooling applications	Chua et al. (1999), Ford and Despeisse (2016), Rylands et al. (2016)
Rapid manufacturing applications (final products)	Gebler et al. (2014), Tien (2012), Tien (2015), Waller and Fawcett (2013)
Healthcare industry, customized medical devices and surgical tools	Emelogu et al. (2016), Giannatsis and Dedoussis (2009), Holmström et al. (2017), Huang et al. (2013), Moore et al. (2016), Oettmeier and Hofmann (2016), Weller et al. (2015)
Manufacturing industry, lightweight or geometrically complex industrial parts and assemblies	Atzeni and Salmi (2012), Khajavi et al. (2015), Rylands et al. (2016), Sasson and Johnson (2016), Yang and Zhao (2015)
Aeronautics industry, lightweight parts and assemblies	Gebler et al. (2014)
Highly customized products	Mohr and Khan (2015), Weller et al. (2015)
Personalized construction of houses	Ford and Despeisse (2016), Kothman and Faber (2016), Wagner and Walton (2016)
Personalized consumer products	Bogers et al. (2016), Chiu and Lin (2016), Eyers and Potter (2015), Jia et al. (2016), Petrick and Simpson (2013), Thiesse et al. (2015)
Spare parts	Chekurov and Salmi (2017), Meisel et al. (2016)
Spare part in aeronautics industry	Khajavi et al. (2014), Liu et al. (2014), Pérès and Noyes (2006)
Design and production phases concur	Holmström et al. (2016), Weller et al. (2015)
AM suitable for small products	Walter et al. (2004)
Manufacturing of products in short-supply	Holmström and Partanen (2014), Pérès and Noyes (2006)
Low-demand or single unit demand	Berman (2012), Chiu and Lin (2016), Holmström et al. (2017), Mellor et al. (2014), Mohr and Khan (2015), Petrick and Simpson (2013), Thiesse et al. (2015)
Spare parts	Fawcett and Waller (2014), Holmström et al. (2010), Holmström and Partanen (2014), Liu et al. (2014), Meisel et al. (2016), Pérès and Noyes (2006), Weller et al. (2015)
Tools	Chua et al. (1999), Ford and Despeisse (2016)
Parts and assemblies	Atzeni and Salmi (2012), Ford and Despeisse (2016), Raja et al. (2006)
Customized consumer products, e.g. lamps	Chiu and Lin (2016)
Big spikes and drops in demand	Ford and Despeisse (2016), Liu et al. (2014), Raja et al. (2006)
AM for art, hobby, fashion, jewelry and education	Maresch and Gartner (2018)

2.3.2 AM and SC design

This section refers to RQ2 and explains how AM affects SC design in terms of the SCOR elements.

2.3.2.1 Plan

AM may change SC networks in terms of the duration and arrangement of the SC steps. Supply chains may be disintermediated (Mills and Camek, 2004), making SCs more concise and straightforward. Petrick and Simpson (2013) refer to a shift in the design-build-deliver sequence, since delivery of basic materials can occur prior to designing and manufacturing on the customer site. AM enables a shift from physical inventory to digital inventory. This may influence assortment decisions due to the ability to replace a range of different stock-keeping units (SKUs).

We call choices related to the positioning of AM in the chain 'SC configuration choices'. Different SC configurations can be found in the literature; distributed manufacturing is the most frequently mentioned. Chekurov and Salmi (2017) point out that local demand needs to be sufficient in order to justify distributed manufacturing. Since digital files and basic materials can be transported more easily than physical products, and no specific knowledge is required locally, distributed AM can be used for in-situ production of (spare) parts in hard to reach places. Examples include places that are hard to access due to poor infrastructure, bribery, distance, danger or geography. Central manufacturing configurations have also been proposed, as well as a mix of central and distributed manufacturing. A case can be made for distributed manufacturing combined with central coordination. The advantages include central order entry and central customer interaction, and at the same time a reduction in transportation costs and time. Moreover, distributed manufacturing can be combined with central digital design, with the advantage of bundling the required modeling competencies. Durão et al. (2017) distinguish between differing levels of central control within distributed AM, and describe a centrally controlled, fully automated distributed AM production location as a 'Cyber Physical Production System'. In contrast, it is also possible to opt for central manufacturing and distributed scanning, e.g. at a retail location with direct access to consumers. Ownership of local facilities can be held by the consumer. The replacement of central warehousing with centralized AM configurations will likely constitute a first step in AM applications. Over time, this may develop into distributed AM configurations. Rayna and Striukova (2016) consider distributed manufacturing as an in-between step towards personalized manufacturing, where production and consumption both occur at the user's home. Ryan et al. (2017) mention mobile AM which is flexible, and easy to re-position close to (changing) demand. This allows for production close to the point of use, in-transit manufacturing, and for manufacturing to follow demand. An example of mobile AM is the in-situ production of components for houses.

When AM replaces traditional manufacturing, the OPP often changes from make-to-stock (MtS) to make-to-order (MtO) or engineer-to-order (EtO). Rather unexpectedly, MtS applications are also mentioned in relation to (aeronautics) spare parts and medical applications. Here, product unavailability may have serious consequences (e.g. airplane downtime or patient trauma), and MtO AM production may still take too long. Holmström et al. (2016) suggest the use of distributed stock-keeping for aircraft spare parts that are immediately required. To ensure aircraft uptime and relatively long AM production lead-times (+/- 48 h), restocking is fulfilled from central AM production with MtS. For spares that are not immediately required, distributed AM with MtO production is suggested as the better option. In contrast, Emelogu et al. (2016) suggest the use of MtO AM production for personalized biomedical implants that may be required immediately (i.e. in life or death situations). The lead-time of conventionally-manufactured patient-specific products can take up to several months, and AM can significantly shorten this period. Table 2.2 provides a list of relevant references.

Table 2.2: Plan literature

Topic	References
SC disintermediation	Mills and Camek (2004)
Concise and straightforward SC	Gebler et al. (2014), Holmström and Partanen (2014), Holmström et al. (2016), Kothman and Faber (2016), Li et al. (2017), Meisel et al. (2016), Mohr and Khan (2015), Tien (2012).
Design-build-deliver sequence shift	Petrick and Simpson (2013)
Replace a range of different SKUs	Berman (2012), Chen (2016), Meisel et al. (2016), Mohr and Khan (2015), Pérès and Noyes (2006), Weller et al. (2015), Yang and Zhao (2015)
Distributed manufacturing	Bogers et al. (2016), Durach et al. (2017), Durão et al. (2017), De la Torre et al. (2016), Holmström et al. (2017), Mohr and Khan (2015), Moore et al. (2016)
Sufficient local demand required	Chekurov and Salmi (2017)
Easy basic materials transportation & no specific local knowledge required	Chekurov et al. (2018)
Hard to reach places	De la Torre et al. (2016), Holmström et al. (2017), Ryan et al. (2017)
Distributed manufacturing with central coordination	Eyers and Potter (2015)
Distributed manufacturing with central design	Oettmeier and Hofmann (2016)
Cyber Physical Production System	Durão et al. (2017)
Local facilities owned by the consumer	Bogers et al. (2016), Eyers and Potter (2015), Steenhuis and Pretorius (2016)
Distributed manufacturing as an in-between step towards personalized manufacturing	Rayna and Striukova (2016)

Table 2.2 continues on next page.

Table 2.2: Plan literature *(continued)*

Topic	References
Central manufacturing	Emelogu et al. (2016), Eyers and Potter (2015), Holmström et al. (2010), Khajavi et al. (2014), Mellor et al. (2014), Rylands et al. (2016)
Central manufacturing and distributed scanning	Rogers et al. (2016)
Centralized AM replaces central warehousing	Walter et al. (2004)
Mix of central and distributed manufacturing	Jia et al. (2016), Li et al. (2017), Liu et al. (2014), Neely (2016).
Mobile AM, in-situ production of components for houses	Kothman and Faber (2016), Ryan et al. (2017)
OPP Shift	
From MtS to MtO	Giannatsis and Dedoussis (2009), Holmström and Partanen (2014), Holmström et al. (2016), Pérès and Noyes (2006)
Immediately required biomedical implants	Emelogu et al. (2016)
From MtS to EtO	Oettmeier and Hofmann (2016), Rylands et al. (2016)
MtO AM production may still take too long	Holmström et al. (2010), Khajavi et al. (2014), Liu et al. (2014)
MtS applications	Khajavi et al. (2014), Liu et al. (2014)
Immediately required aircraft spare parts	Holmström et al. (2016)

2.3.2.2 Source

The availability of basic material is one of the key enabling components of an AM SC. Maresch and Gartner (2018) mention a preference for plastics, since plastic is cheap and can be used for various applications. Metals are increasingly important for industrial applications but may at some point be replaced by high performance polymers or ceramics. In fact, many other materials are printable, and each material has its specific pros and cons. In AM, fewer basic materials may be sourced as compared to CM methods. Kothman and Faber (2016) estimate that concrete (volume) savings of 50-60% can be made in the construction industry due to the ability to print hollow structures. Thiesse et al. (2015) estimate that a saving of 30% in material weight can be achieved in a manufacturing context. A shift to local supply of basic materials is also highlighted in the literature. There are hurdles related to the basic materials used that can prevent the roll-out of AM. These include the high costs of materials, poor material characteristics, variable quality across shipments due to a lack of standardization, and a limited variety of available materials (due to the complexity and cost of new material development). Indeed, when compared to CM, the amount of materials available for AM is very limited. Kretzschmar et al. (2018) expect that many more printable materials will become commercialized, since several materials are already printable in research environments but not yet available in the industry. Ngo et al. (2018) note that the

limited amount of printable metals has led to the development of (printable) alloys and composites. Finally, Weller et al. (2015) highlight the fact that different materials are not currently combined in the print process, something they consider to be a limitation.

Kothman and Faber (2016) argue that AM requires fewer partners – but close cooperation with these partners, for instance in relation to quality control. In line with this, Chekurov et al. (2018) mention that material and software suppliers are significantly more important in digital spare parts processes than they were traditionally. As a consequence, compared to CM, AM will reduce the dependency on component suppliers but increase dependency on basic material and IT suppliers, due to a lack of competition.

Outsourcing to an AM service provider (capacity pooling) is a business practice that can be used to overcome inefficiencies in utilizing AM machines belonging to individual companies. Chekurov et al. (2018) state a preference for an international service provider network with central storage of digital spare parts, and AM production close to the customer. This requires a sufficiently robust (digital) distribution method. Choosing between inventory keeping, local manufacturing or outsourcing to an AM service provider is a decision that should be taken based on calculations. Bogers et al. (2016) and Rogers et al. (2016) mention the risk of knowledge leaks – in particular when manufacturing is outsourced to an AM service provider. In line with this, Chekurov et al. (2018) mention the risk of piracy through data leaks or the reverse engineering of components. The full list of references is provided in Table 2.3.

Table 2.3: Source literature

Topic	References
Basic material	
Preference for plastics	Maresch and Gartner (2018)
Fewer basic materials sourced as compared to CM	Barz et al. (2016), Berman (2012), Ford and Despeisse (2016)
50-60% concrete (volume) savings (construction industry)	Kothman and Faber (2016)
30% material weight reduction in manufacturing	Thiesse et al. (2015)
Shift to local supply	Bogers et al. (2016), Chen (2016), Ford and Despeisse (2016), Petrick and Simpson (2013), Rylands et al. (2016)
Bottleneck: poor availability/limited variety	Atzeni and Salmi (2012), Durach et al. (2017), Gebler et al. (2014), Kretzschmar et al. (2018), Moore et al. (2016), Ngo et al. (2018)
Bottleneck: materials not often combined	Weller et al. (2015)
Bottleneck: high costs	Berman (2012), Durach et al. (2017), Dwivedi et al. (2017), Waller and Fawcett (2014)
Bottleneck: poor material characteristics	Petrick and Simpson (2013), Steenhuis and Pretorius (2016), Wagner and Walton (2016)
Bottleneck: variable quality across shipments	Chekurov et al. (2018)

Table 2.3 continues on next page.

Table 2.3: Source literature *(continued)*

Topic	References
Partners in SC	
Fewer partners required	Kothman and Faber (2016)
Close cooperation required	De la Torre et al. (2016), Oettmeier and Hofmann (2016), Petrick and Simpson (2013)
Material and software more important	Chekurov et al. (2018)
Reduced dependency on component suppliers; increased dependency on basic material and IT suppliers	Barz et al. (2016), Berman (2012), Ford and Despeisse (2016), Holmström et al. (2010), Holmström et al. (2016), Mellor et al. (2014), Rylands et al. (2016)
Outsourcing to an AM service provider	Berman (2012), Holmström et al. (2010), Holmström and Partanen (2014), Rogers et al. (2016), Wagner and Walton (2016)
International service provider network	Chekurov et al. (2018)
Choice between inventory keeping, local manufacturing or outsourcing	Knofius et al. (2016), Ryan et al. (2017)
Risk of knowledge leaks	Bogers et al. (2016), Rogers et al. (2016)
Risk of piracy	Chekurov et al. (2018)

2.3.2.3 Make

AM production is an obvious key enabling component of AM SCs. ISO/ASTM (2015) standardizes AM definitions and distinguishes between the following production process categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. In the 1980s, the first techniques – laminated object manufacturing, fused deposition modelling, selective laser sintering and stereo lithography – were developed and were, in the early 1990s, used for rapid-prototyping. In the second half of the 1990s, the AM processing of metal alloys and heat resistant polymers allowed for rapid-tooling applications – thus increasing manufacturing speed and reducing manufacturing costs of e.g. molds. Rapid-prototyping and rapid-tooling applications can be considered 'mature' and have incrementally improved existing business models and supply chains. When costs lowered and quality improved in the late 2000s, (direct) digital manufacturing of final products also became possible, either by the manufacturer in-house, or outsourced to an AM service provider. This phase has not yet reached maturity, but – when fully developed – this phase may disrupt existing business models and supply chains. Currently, several online AM service provider platforms already exist (e.g. materialise.com, shapeways.com and oceanz.eu). The final stage of AM adoption is home fabrication – where consumers manufacture products themselves with self-owned AM equipment. The development of this new phase is uncertain (currently it is mainly hobbyists and engineering students involved in this phase) (Rayna and Striukova, 2016).

The use of AM can result in fewer production steps (disintermediation) and can therefore reduce the amount, capacities and capital invested in production facilities and equipment. There is an expectation in the majority of the literature that, over time, AM will replace CM. Others see AM as an innovative solution or propose hybrid designs where AM and CM are used in combination. Several hybrid alternatives can be distinguished in the literature. In one scenario, AM and CM complement each other. An example of this is the production of standard products on a conventional line while specialty items are produced on an AM line. AM can also be used to optimize scale economies of mass-manufacturing. CM can be used to produce quick runners, while AM can be used for slow runners. Alternatively, AM can be used for variable production, aiding CM. A final hybrid design involves 'bridging' the product development phase to the mass-manufacturing phase. In this scenario, AM starts early production and, when proven feasible, CM is selected. In this way, product design can be improved and tool choices are delayed until demand is clear. Moreover, AM can produce early sales during CM ramp-up. However, according to Holmström et al. (2016), the decision regarding when to switch from early production AM to mass-manufacturing remains a challenge. Walter et al. (2004) suggest a procedure for assessing the suitability of parts for AM. Knofius et al. (2016) take this a step further, and propose a scoring method to identify spare parts that would benefit from AM production.

Many AM production-related bottlenecks were found in the literature. We distinguish between product-, processing- and regulation-related bottlenecks. Product bottlenecks refer to limitations in strength, durability, consistency, product safety, product accuracy and (surface) quality of products. Chekurov and Salmi (2017) refer to the production of a polyamide AM spare part with a rough surface, and argue that the surface quality needs to improve in order to widen the range of AM applications. Kretzschmar et al. (2018) mention that (unwanted) post-processing activities are needed to compensate for low 3D print accuracy levels. The literature suggests that these issues are particularly relevant for aeronautics, manufacturing and business-to-consumer environments.

AM processing-related bottlenecks refer to low automation levels, slow production time (building speed), low throughput, and high equipment and manufacturing costs. Also mentioned is the limited size of the components due to the production chamber size, and the instability and unreliability of the print process. Mellor et al. (2014) describe machine manufacturers locking down machine parameters – thus limiting manipulation and innovation by the users. Chekurov et al. (2018) add that parts are not ready after 3D printing, and require post-processing. They also add the imprecision of 3D scanning to the list of bottlenecks. Ngo et al. (2018) mention that the layer-by-layer application of material can cause the formation of voids which negatively affects the

mechanical properties. It is also worth noting that the mechanical properties in vertical and horizontal directions can be different (anisotropy).

Regulation-related bottlenecks also exist. The most frequently mentioned bottleneck is ambiguity about intellectual property (IP) rights, which appears to be relevant in both business-to-business and business-to-consumer contexts. Other regulation bottlenecks identified in the literature include the absence of component certification, liability, warranty and biocompatibility. Moreover, authors point out that new regulations are required for quality assurance (QA), process certification, process qualification, and testing and inspection for application in healthcare, the aeronautics industry, the energy industry, and for spare parts. References are provided in Table 2.4.

Table 2.4: Make literature

Topic	References
Standard AM definitions	ISO/ASTM (2015)
Different levels of AM maturity	Rayna and Striukova (2016)
Reduced amount, capacities and capital invested in production facilities and equipment	Ford and Despeisse (2016), Holmström and Partanen (2014), Khajavi et al. (2014), Mohr and Khan (2015), Thiesse et al. (2015), Weller et al. (2015), Yang and Zhao (2015)
AM replaces CM	Eyers and Potter (2015), Holmström et al. (2010), Holmström and Partanen (2014), Mohr and Khan (2015), Thiesse et al. (2015)
AM as an innovative solution	Bogers et al. (2016), Ford and Despeisse (2016), Pérès and Noyes (2006), Petrick and Simpson (2013)
Hybrid: AM and CM complement each other	Holmström et al. (2017), Wagner and Walton (2016)
Standard products on a conventional line; specialty items on an AM line	Rylands et al. (2016)
CM for quick runners, AM for slow runners	Sasson and Johnson (2016)
AM for variable production, aiding CM	Chiu and Lin (2016)
Bridging product development to mass-manufacturing	Khajavi et al. (2015)
Switching from early production AM to mass-manufacturing	Holmström et al. (2016)
Assessing suitability of parts for AM.	Knofius et al. (2016), Walter et al. (2004)
Product-related bottlenecks	
(Surface) quality of products	Chekurov and Salmi (2017), Durach et al. (2017), Eyers and Potter (2015), Steenhuis and Pretorius (2017), Steenhuis and Pretorius (2016), Wagner and Walton (2016), Yang and Zhao (2015)
Accuracy	Berman (2012), Ford and Despeisse (2016), Kothman and Faber (2016), Kretzschmar et al. (2018), Moore et al. (2016)

Table 2.4 continues on next page.

Table 2.4: Make literature *(continued)*

Topic	References
Strength	Chiu and Lin (2016), Dwivedi et al. (2017), Moore et al. (2016)
Durability	Chiu and Lin (2016)
Consistency	Dwivedi et al. (2017)
Product safety	Neely (2016)
Aeronautics industry	Ford and Despeisse (2016), Moore et al. (2016), Wagner and Walton (2016)
Manufacturing industry	Yang and Zhao (2015)
B2C environments	Chiu and Lin (2016), Kothman and Faber (2016), Neely (2016), Steenhuis and Pretorius (2016)
Production-related bottlenecks	
Low automation	Ford and Despeisse (2016), Kothman and Faber (2016)
Slow production	Durach et al. (2017), Dwivedi et al. (2017), Gebler et al. (2014), Wagner and Walton (2016), Yang and Zhao (2015)
Low throughput, high equipment and manufacturing costs	Durach et al. (2017), Dwivedi et al. (2017)
Component size limitations	Chekurov et al. (2018)
Print process instability, unreliability	Durach et al. (2017)
Machine manufacturers locking down machine parameters	Mellor et al. (2014)
Required post-processing, imprecision of 3D scanning	Chekurov et al. (2018)
Issues related to mechanical properties	Ngo et al. (2018)
Regulations-related bottlenecks	Huang et al. (2013), Moore et al. (2016)
IP rights ambiguity	Berman (2012), Eyers and Potter (2015), Rogers et al. (2016), Thiesse et al. (2015)
Business-to-business contexts	Holmström et al. (2010), Holmström and Partanen (2014), Holmström et al. (2016), Wagner and Walton (2016)
Business-to-consumer contexts	Neely (2016), Petrick and Simpson (2013)
Component certification	Ford and Despeisse (2016)
Liability	Ford and Despeisse (2016), Holmström et al. (2016), Thiesse et al. (2015)
Warranty	Holmström et al. (2016)
Biocompatibility	Durach et al. (2017)
QA regulations	Thiesse et al. (2015)
Process certification & qualification	Sirichakwal and Conner (2016)
Testing & inspection	Petrick and Simpson (2013)
Healthcare industry	Moore et al. (2016)
Aeronautics, energy industries, spare parts	Ford and Despeisse (2016), Holmström et al. (2010), Wagner and Walton (2016)

2.3.2.4 Deliver

Central storage of digital files can replace the warehousing of tangible products. Moreover, AM can shift inventories from finished goods to basic materials, and can shorten production lead-time. This requires adjustments at various points in the distribution system. These changes may include reduced stock, reduced warehousing, reduced material handling, and reduced packaging.

AM allows digital file distribution to largely replace the conventional transportation of goods. Upstream transportation shifts (only) to basic materials and downstream transportation shifts to local finished goods. This may require adaptation of transportation modalities from bulk (trucks) to fine distribution (vans). Overall, AM reduces the need for transportation. In the case of mobile AM, transportation becomes a value-adding process. A full list of references is provided in Table 2.5.

Table 2.5: Deliver literature

Topic	References
Digital files replace tangible products	Chekurov et al. (2018)
Inventories shift from finished goods to basic materials	Barz et al. (2016), Berman (2012), Eyers and Potter (2015), Ford and Despeisse (2016), Holmström et al. (2010), Holmström et al. (2016), Huang et al. (2013), Mohr and Khan (2015), Waller and Fawcett (2014)
Shorter production lead-time	Sirichakwal and Conner (2016)
Distribution system adjustments	Chen (2016), Gebler et al. (2014), Steenhuis and Pretorius (2016)
Reduced stock	Berman (2012), Bogers et al. (2016), Eyers and Potter (2015), Ford and Despeisse (2016), Holmström et al. (2010), Holmström and Partanen (2014), Holmström et al. (2017), Khajavi et al. (2015), Li et al. (2017), Liu et al. (2014), Mohr and Khan (2015), Moore et al. (2016), Sasson and Johnson (2016)
Reduced warehousing	Rogers et al. (2016)
Reduced handling of material	Holmström and Partanen (2014), Huang et al. (2013), Thiesse et al. (2015), Wagner and Walton (2016)
Reduced packaging	Huang et al. (2013)
Digital file distribution replaces conventional transportation of goods	De la Torre et al. (2016), Ford and Despeisse (2016), Holmström et al. (2010)
Upstream transportation shifts (only) to basic materials	Ford and Despeisse (2016), Kothman and Faber (2016)
Downstream transportation shifts to local finished goods	Thiesse et al. (2015)
Adaptation to different transportation modalities	Chen (2016), Petrick and Simpson (2013), Steenhuis and Pretorius (2016)

Table 2.5 continues on next page.

Table 2.5: Deliver literature *(continued)*

Topic	References
Reduced transportation	Barz et al. (2016), Bogers et al. (2016), Eyers and Potter (2015), Holmström and Partanen (2014), Holmström et al. (2017), Huang et al. (2013), Li et al. (2017), Mohr and Khan (2015), Moore et al. (2016), Rogers et al. (2016), Wagner and Walton (2016), Waller and Fawcett (2014)
For mobile AM transportation is value-adding	Ryan et al. (2017)

2.3.2.5 Return

AM can help SCs to become more closed loop. AM's design freedom can reduce disassembly efforts after the products have been used. AM also promotes the use of recycled materials and allows to internally recycle unused powder. Finally, AM can extend the product's life cycle via in situ remanufacturing of machine parts. Table 2.6 provides a full list of references.

Table 2.6: Return literature

Topic	References
Reduced disassembly efforts	Yang and Zhao (2015)
Use of recycled materials	Mohr and Khan (2015)
Internally recycle unused powder	Ford and Despeisse (2016)
Extending product's life cycle	Ford and Despeisse (2016)

2.3.2.6 Enable

Another key enabling component of an AM SC is the availability of a digital file, either a CAD drawing (of the new design) or a scan (of an existing design). Co-creation of these digital files by an engineer and a customer empowers customers to take over certain design tasks. In this scenario, a customer co-creation platform is also an enabling component. These platforms may require an online tool and should enable the sharing and retention of digital files. However, creating a secure IT infrastructure can be a challenge. Moreover, the IT infrastructure of Original Equipment Manufacturers (OEMs) may currently be unable to support digital spare parts distribution, and upgrading IT may require large investments. This in turn is a supporting argument for AM capacity pooling (see Section 2.3.2.2). The ability to combine AM information systems with other electronic services at another location (e.g. sensor-based maintenance information) may be necessary, particularly in relation to hard to reach places. IT system changes may be required due to the shift from conventional inventory management (using a bill of material) to IT systems that enable individual tracking. Moreover, existing digital market places can be used by consumers to sell AM-produced products from their own homes.

AM may affect the way that people work. Compared to CM, in which more complex and varied tools and machines are required, AM requires less knowledge and skills, as well as reduced manual intervention. On the other hand, new AM and digital design knowledge – also called 'design-for-AM knowledge' – is a key enabling component, and a lack of this knowledge is considered to be a potential bottleneck. A reallocation of tasks in the supply chain means that the distinction between roles can disappear and new roles and responsibilities need to be defined. For example, fewer personnel may be required, and overhead costs may be reduced. Production may be carried out by the customer. Dwivedi et al. (2017) identify several potential human resources-related bottlenecks in the implementation of AM, namely the required attitude change (of traditional designers), the unavailability of skilled operators, workers' resistance to change, inadequate government and management support, lack of knowledge regarding AM cost calculation, and a lack of trust in the machine and material suppliers. Durach et al. (2017) also mention customer awareness and acceptance as possible bottlenecks. A full list of references is provided in Table 2.7.

Table 2.7: Enable literature

Topic	References
IT systems	
Customers taking over aspects of design	Bogers et al. (2016), Eyers and Potter (2015), Ford and Despeisse (2016), Holmström et al. (2017), Petrick and Simpson (2013), Rylands et al. (2016), Thiesse et al. (2015)
Platforms and sharing and retention of digital files	Berman (2012), De la Torre et al. (2016), Ford and Despeisse (2016), Giannatsis and Dedoussis (2009), Holmström et al. (2010), Mohr and Khan (2015), Pérès and Noyes (2006), Petrick and Simpson (2013), Rylands et al. (2016), Waller and Fawcett (2013)
Online tools	Eyers and Potter (2015), Gebler et al. (2014)
Secure IT infrastructure	Rogers et al. (2016).
Existing IT infrastructure issues	Chekurov et al. (2018)
Combinations with other electronic services	Pérès and Noyes (2006), Tien (2012), Tien (2015)
IT system changes related to individual tracking	Holmström et al. (2016), Thiesse et al. (2015)
Existing digital market places	Ryan et al. (2017)
People	
Less knowledge and skills required	Mohr and Khan (2015), Thiesse et al. (2015)
Reduced manual intervention	Weller et al. (2015)
Lack of new AM and digital design knowledge is a bottleneck	Durach et al. (2017), Oettmeier and Hofmann (2016), Thiesse et al. (2015)
New roles and responsibilities	Kothman and Faber (2016), Mohr and Khan (2015), Petrick and Simpson (2013)
Fewer personnel and reduced overhead costs	Emelogu et al. (2016), Khajavi et al. (2014)

Table 2.7 continues on next page.

Table 2.7: Enable literature *(continued)*

Topic	References
Production by the customer	Bogers et al. (2016), Eyers and Potter (2015), Steenhuis and Pretorius (2016)
Bottlenecks: attitude change, operator unavailability, resistance to change, inadequate support, lack of knowledge, lack of trust	Dwivedi et al. (2017)
Bottlenecks: customer awareness and acceptance	Durach et al. (2017)

2.3.3 AM and SC performance outputs

This section relates to RQ3 and describes how AM influences the desired (or sometimes unwanted) SC performance outputs. Rogers et al. (2017) expect SC performance to improve over time alongside the increasing maturity of AM technology.

2.3.3.1 Costs

Reducing costs seems to be the main advantage of AM. Inventory reductions are most frequently reported, i.e. reductions in stored basic materials, finished goods, or both. Specifically mentioned are reductions in safety stock, obsolescence rates and work-in-process. Lowering of production costs may also be achievable. Walter et al. (2004) note that AM is primarily cost effective for small parts, since cost mainly depends on the volume of parts and the related high variable costs of basic materials and the layer-by-layer building process. Reductions in production costs include reductions in assembly costs, set-up costs, energy costs, material handling costs, personnel costs, and packaging and water costs, as well as improved resource efficiency. Holmström et al. (2017) and Weller et al. (2015) mention 'customization without extra cost' as an advantage. By contrast, Waller and Fawcett (2013) argue that AM is less efficient than mass production. However, unavailability costs – e.g. downtime costs and penalties due to a missing aircraft spare part- may easily outweigh the higher single-piece production costs. Chua et al. (2005) explain this 'economies-of-scale dilemma' by the absence of specific tools to be amortized over the batch, making the production of small series or single unit production through AM much cheaper. To illustrate this, they point to a 30,000US$ tooling and 0.20US$ piece cost for CM as compared to a 0US$ tooling and 130US$ piece cost for AM. Giannatsis and Dedoussis (2009) explain that high production costs can occur with the application of expensive AM production techniques and argue that costs can be reduced when using cheaper AM techniques. Li et al. (2017) agree that AM production costs are higher, due to expensive labor and high basic material costs (per weight unit). However, they argue that overall SC costs will be lower due to the reduced need for transportation and the fact that AM requires fewer basic materials than CM. Indeed, as indicated in Section 2.3.2.4, AM may well reduce transportation costs. Obviously, central AM can lead to higher transportation costs than distributed AM.

AM may reduce operations costs during use. Moreover, Ford and Despeisse (2016) mention AM's shape freedom which allows for the design of lightweight components that can save fuel during airplane operation. Unavailability costs can be reduced by improving availability through the in-situ production of spare parts – for instance in hard to reach places, e.g. for trucks used in humanitarian aid. A full list of references is provided in Table 2.8.

Table 2.8: Cost literature

Topic	References
Inventory cost reductions	Bogers et al. (2016), Emelogu et al. (2016), Li et al. (2017), Wagner and Walton (2016), Waller and Fawcett (2014)
Basic materials	Atzeni and Salmi (2012), Chiu and Lin (2016), Eyers and Potter (2015), Ford and Despeisse (2016), Holmström et al. (2010), Holmström et al. (2016), Huang et al. (2013), Kothman and Faber (2016), Mellor et al. (2014), Mohr and Khan (2015), Petrick and Simpson (2013), Thiesse et al. (2015)
Finished goods	Atzeni and Salmi (2012), Berman (2012), Eyers and Potter (2015), Ford and Despeisse (2016), Holmström et al. (2010), Holmström et al. (2017), Kothman and Faber (2016), Mohr and Khan (2015), Rylands et al. (2016)
Safety stock	Berman (2012), Liu et al. (2014), Sasson and Johnson (2016)
Obsolescence rates	Holmström and Partanen (2014), Khajavi et al. (2015), Mohr and Khan (2015)
Work-in-process	Rylands et al. (2016)
AM cost effective for small parts	Walter et al. (2004)
Lower production costs	Chin (1998), Chua et al. (1999), Fawcett and Waller (2014), Ford and Despeisse (2016), Gebler et al. (2014), Mohr and Khan (2015), Raja et al. (2006), Yang and Zhao (2015)
Assembly costs	Atzeni and Salmi (2012), Holmström and Partanen (2014), Weller et al. (2015)
Set-up costs	Holmström et al. (2016), Sasson and Johnson (2016)
Energy costs	Baumers et al. (2013)
Material handling costs	Holmström and Partanen (2014), Huang et al. (2013)
Personnel costs	Khajavi et al. (2014), Thiesse et al. (2015),
Packaging and water costs	Huang et al. (2013)
Improved resource efficiency	Thiesse et al. (2015)
Customization without extra cost	Holmström et al. (2017), Weller et al. (2015)
Less efficient than mass production	Waller and Fawcett (2013)
Unavailability costs outweigh higher single-piece costs	Berman (2012), Pérès and Noyes (2006)
Economies-of-scale dilemma	Chua et al. (2005)
Costs reductions when using cheaper AM techniques	Giannatsis and Dedoussis (2009)
Lower overall SC costs due to the reduced transportation and fewer basic materials	Li et al. (2017)

Table 2.8 continues on next page.

Table 2.8: Cost literature *(continued)*

Topic	References
Reduced transportation costs	Barz et al. (2016), Bogers et al. (2016), Eyers and Potter (2015), Ford and Despeisse (2016), Huang et al. (2013), Mohr and Khan (2015), Waller and Fawcett (2014)
Higher transportation costs for central than for distributed AM	Holmström et al. (2010), Khajavi et al. (2014)
Reduced costs during use	Bogers et al. (2016), Chiu and Lin (2016), Gebler et al. (2014), Giannatsis and Dedoussis (2009)
Lightweight components save fuel during airplane operation	Ford and Despeisse (2016)
Reduction in unavailability costs	De la Torre et al. (2016), Pérès and Noyes (2006)

2.3.3.2 Assets

Assets in supply chains may be affected since AM does not require product-unique equipment. Possible outcomes include a reduction in the need for tools, machines, and certain facilities. The lifecycle of assets may be extended – for example, Holmström et al. (2017) describe the potential future integration of sensor technology and Ford and Despeisse (2016) mention in-situ turbine blades refurbishment. A full list of references is provided in Table 2.9.

Table 2.9: Assets literature

Topic	References
Reduced need for tools	Atzeni and Salmi (2012), Berman (2012), Chin (1998), Chua et al. (2005), Holmström et al. (2016), Khajavi et al. (2015), Waller and Fawcett (2013)
Reduced need for machines	Khajavi et al. (2014)
Reduced need for facilities	Mohr and Khan (2015), Thiesse et al. (2015)
Extended lifecycle	Ford and Despeisse (2016), Holmström et al. (2017)

2.3.3.3 Responsiveness

AM may improve SC responsiveness by making products more quickly available. This can occur as a result of, for example, faster design (reducing time-to-market), or faster production of complex component geometries in e.g. the aeronautics or healthcare industries. Vinodh et al. (2010) report that rapid prototyping (as compared to conventional prototyping) can bring (total) production time down from six days to two days and six hours. Chua et al. (2005) suggest that AM can lower production lead-time from 12 weeks to two days. Rylands et al. (2016) report that, using AM, production of highly customized co-created industrial parts can take just one week and cost several

hundred pounds – as compared to six months and 15,000 pounds using CM. Due to the ability to produce in an integrated (assembled) state, AM may reduce assembly time. Positive effects on repair times are also mentioned in the literature. Ford and Despeisse (2016) suggest that in-situ AM remanufacturing of machine parts is up to ten times faster than traditional repair. Chekurov and Salmi (2017) suggest that repair time can be reduced from 14 days to three days by printing a polyamide computer spare part in a repair shop instead of obtaining the part through conventional distribution channels. A full list of references is provided in Table 2.10.

Table 2.10: Responsiveness literature

Topic	References
Reduced time-to-market; faster production of complex geometries	Giannatsis and Dedoussis (2009), Meisel et al. (2016), Oettmeier and Hofmann (2016), Petrick and Simpson (2013), Ryan et al. (2017)
Rapid prototyping production in two days and six hours instead of six days	Vinodh et al. (2010)
Reduced production lead-time from 12 weeks to two days	Chua et al. (2005)
Production of customized industrial parts in one week as compared to six months	Rylands et al. (2016)
Reduced assembly time	Atzeni and Salmi (2012), Yang and Zhao (2015)
Reduced repair times	De la Torre et al. (2016), Emelogu et al. (2016), Khajavi et al. (2014), Pérès and Noyes (2006), Wagner and Walton (2016)
Ten times faster in-situ AM remanufacturing	Ford and Despeisse (2016)
Reduced repair time from 14 days to three days	Chekurov and Salmi (2017)

2.3.3.4 Reliability

Although bottlenecks still exist, AM may improve the quality and reliability of high-performance complex parts e.g. parts used in healthcare and aeronautics. This is because designer-customer collaboration and (learning by) fast iterations leads to high-quality design. AM may allow for production in one piece, and the absence of assembly, joining or welding may lead to higher-quality products. Kothman and Faber (2016) mention improved reliability associated with in-situ production of construction parts, due to reduced transportation damage. Holmström et al. (2016) suggest that using shorter supply chains can lead to improved reliability in terms of delivery dates. Moreover, the availability of products may improve when in-situ AM is used. Oettmeier and Hofmann (2016) point to the improved replicability of hearing aids due to the availability of a digital design, and Giannatsis and Dedoussis (2009) mention preoperative models in healthcare designed to improve consent and trust. A full list of references can be found in Table 2.11.

Table 2.11: Reliability literature

Topic	References
Fast iterations lead to high-quality design	Atzeni and Salmi (2012), Fawcett and Waller (2014), Ford and Despeisse (2016), He et al. (2006), Holmström et al. (2017)
Absence of assembly, joining or welding leads to higher-quality products	Giannatsis and Dedoussis (2009), Huang et al. (2013), Rylands et al. (2016)
In-situ production of construction parts leads to improved reliability	Kothman and Faber (2016)
Improved delivery dates leads to improved reliability	Holmström et al. (2016)
Improved availability of products in hard to reach places	De la Torre et al. (2016), Pérès and Noyes (2006)
Improved replicability of hearing aids	Oettmeier and Hofmann (2016)
Preoperative models in healthcare leads to improved consent and trust	Giannatsis and Dedoussis (2009)

2.3.3.5 Flexibility

Product and volume manufacturing flexibility improves by using AM. In contrast to CM – where large minimum order quantities (e.g. 1000 pieces) are the standard – in AM, single pieces or small series in a wide range of stock keeping units (SKUs) can be produced using one process. This also makes it possible to improve or extend the product mix. AM can support the management of demand fluctuations. Ryan et al. (2017) describe mobile AM as a flexible AM application, and Pérès and Noyes (2006) illustrate this with an example of the production of military spare parts. A full list of references is provided in Table 2.12.

Table 2.12: Flexibility literature

Topic	References
Wide range of SKUs produced using one process	Li et al. (2017), Meisel et al. (2016), Weller et al. (2015)
Improve or extend the product mix	Steenhuis and Pretorius (2017)
Improved management of demand fluctuations	Chiu and Lin (2016)
Mobile AM is a flexible AM application	Pérès and Noyes (2006), Ryan et al. (2017)

2.3.3.6 Risks

Positive effects in terms of risks include a reduced risk of law suits due to better design quality, improved safety due to personalized health care products, reduction of stock-out risk and reduced risks related to infection and anesthesia in a hospital setting. However, data transfer via unsecured connections may increase the risk of knowledge leaks. Moreover, in Section 3.2.2 we mentioned reduced risks in terms of a decreased dependency on (component) suppliers while, due to lack of competition, there may

be increased risks associated with a greater dependency on basic material suppliers. A full list of references is provided in Table 2.13.

Table 2.13: Risks literature

Topic	References
Reduced risk of law suits	Khajavi et al. (2015)
Improved healthcare safety	Huang et al. (2013)
Reduced stock-out risk	Sirichakwal and Conner (2016)
Reduced risks related to infection and anesthesia	Giannatsis and Dedoussis (2009)
Increased risk of knowledge leaks	Bogers et al. (2016)
Decreased dependency on (component) suppliers but greater dependency on basic material suppliers	Barz et al. (2016), Holmström et al. (2010), Holmström et al. (2016), Mellor et al. (2014)

2.3.3.7 Sustainability

As mentioned in the previous sections, AM may positively affect sustainability – for instance, by extending the lifecycle of products. Also, AM only uses material where it is needed and therefore requires fewer basic materials, reducing energy, emissions, waste (materials), pollution, and landfill, which results in a smaller carbon footprint. Baumers et al. (2013) suggest that the single-step nature of AM simplifies energy measurement which can stimulate minimal energy consumption. Li et al. (2017) mention that although AM manufacturing and material preparation consumes considerably more energy, the total AM supply chain consumes considerably less energy due to reduced transportation and material use. Gebler et al. (2014) and Holmström et al. (2017) suggest that AM enables re-industrialization in Western countries whereby local AM enables labor to be sourced near the point of consumption rather than from low wage countries. Holmström et al. (2017) argue that AM applications for medical devices can improve social sustainability outcomes. A full list of references is provided in Table 2.14.

Table 2.14: Sustainability literature

Topic	References
Extension of the lifecycle of products	Ford and Despeisse (2016)
Reduced energy, emissions, waste, pollution, landfill, smaller carbon footprint	Berman (2012), Chiu and Lin (2016), Kothman and Faber (2016), Rylands et al. (2016), Yang and Zhao (2015)
Simplified energy measurement which stimulates minimal energy consumption	Baumers et al. (2013)
Total SC consumes less energy	Li et al. (2017)
Re-industrialization in Western countries	Gebler et al. (2014), Holmström et al. (2017)
Improved social sustainability outcomes	Holmström et al. (2017)

2.3.3.8 Innovation

AM may have a positive effect on innovation. The ability to create new shapes (via integrated or new functions) can lead to new or improved products or services, for instance, Kothman and Faber (2016) mention integrated cooling channels in construction. AM may simplify the process of adjusting products in line with customer preferences, allowing customization through co-creation. However, this carries the risk of 'customer lock-in'. Holmström et al. (2017) mention the potential introduction of new technologies during refurbishment of products already in use. In line with this, Chekurov et al. (2018) mention the upgrading of spare parts, including improvements based on field maintenance data. Meisel et al. (2016) suggest that AM can encourage innovation – for example, when using an expeditionary mobile lab in hard to reach places. A full list of references is provided in Table 2.15.

Table 2.15: Innovation literature

Topic	References
New or improved products or services	Holmström and Partanen (2014), Oettmeier and Hofmann (2016), Steenhuis and Pretorius (2017), Thiesse et al. (2015)
Integrated cooling channels	Kothman and Faber (2016)
Customization through co-creation	Durach et al. (2017), Jia et al. (2016), Petrick and Simpson (2013), Waller and Fawcett (2014), Weller et al. (2015)
Risk of 'customer lock-in'	Rylands et al. (2016)
Introduction of new technologies during refurbishment of products already in use	Holmström et al. (2017)
Upgrading of spare parts based on field maintenance data	Chekurov et al. (2018)
Encourage innovation	Meisel et al. (2016)

2.3.4 Conceptual framework

Based on Sections 2.3.1 through 2.3.3, this section presents the propositions and the conceptual relationships according to the IPO model, as illustrated in Figure 2.1. This section relates to RQ4 and outlines the cause and effect relationships between SC design in terms of input (I), the transformation process (P) and the resulting output (O). Note that propositions are valid only if the bottlenecks are overcome.

2.3.4.1 Plan propositions

1. Distributed SC configurations (I) are possible since AM uses digital files that travel more easily than physical products, a universal basic material is used, and no specific production equipment and knowledge is required (P). Distributed SC configurations (compared to centralized SC configurations) require higher

investments in assets (distributed AM machines) and higher local market volume, but offer lower transportation costs and faster delivery (O);

2. Distributed AM SC configurations are particularly suited to 'hard-to-reach places' (I). Digital file transfer, the use of just one kind of basic material, and the absence of specific machines and knowledge mean that certain hurdles (e.g. bribery or long distances) can be bypassed (P). This improves product availability (O);

3. Mobile AM solutions (I) are enabled by the use of digital files, the use of one universal basic material, and the fact that no specific equipment or knowledge is required (P). This allows a more flexible response to changing demand (O);

4. AM supply chains are simplified and the classic sequence of the SC steps changes, i.e. the processes 'make' and 'deliver', are swapped around (I). This is enabled by the use of digital files, the use of one universal basic material, and the fact that no specific equipment or knowledge is required (P). Such SCs require less assets (such as tools, machines and facilities) (O);

5. AM allows for different OPP choices (I). This is enabled by the storage of inventory in digital files which allows a wide range of SKUs to be replaced by one IT process, thus removing or reducing physical inventory. In turn, this facilitates postponement of the manufacturing decision, shifting the OPP upstream from MtS to MtO. In situations where MtO CM is changed into MtO AM, the OPP shifts downstream. Finished goods inventories downstream are replaced by upstream basic materials stock (P). This reduces the stock-keeping costs, obsolescence risk, warehousing and material handling costs (personnel, transportation), as well as unavailability costs. Moreover, this leads to improved product and volume flexibility (O); Note that MtS AM may exist in situations where product unavailability has serious consequences and MtO AM production takes too long.

2.3.4.2 Source propositions

6. Basic material sourcing decisions (I) relate to the additive nature of AM which reduces the required volume of basic materials, since material is only added where it is needed (P). The benefits include a reduction in the use (and cost) of basic materials and smaller footprints (O);

   Bottlenecks preventing the roll-out of AM are related to the limited availability of a variety of different materials, difficulties in combining different materials, as well as the characteristics, standardization, cost and development of new basic materials.

7. Introducing AM in a SC implies changed relationships with basic material suppliers (I). The additive (vs subtractive) nature of AM means that fewer (types of) basic materials need to be sourced. Moreover, products can be produced from just

one (universal) source (P). This reduces dependency on component suppliers but increases dependency on basic material suppliers (O);

8. Implementing AM in a SC changes relationships with partners in the chain (I). This is caused by AM's ability to produce different shaped products in the same build and allows for the sharing of batches between customers and outsourcing to AM service providers (P). Horizontal SC integration reduces costs for individual companies (O) who, by themselves, lack full utilization of AM equipment;

2.3.4.3 Make propositions

9. Introducing AM machining (I) in a SC changes the capabilities of the physical product since AM allows for the production of complex shapes and enables faster manufacturing of complex geometries. Moreover, the absence of product-unique equipment requires no amortization over large series (P). This brings the cost of (very) small series or single units down, e.g. spare parts in the maturity phase of the life cycle. It also reduces the time-to-market, and allows for faster manufacturing of components (O);

   Introducing AM machining requires the elimination of bottlenecks related to product quality, accuracy, strength (mechanical properties), durability and consistency. Moreover, it requires the elimination of bottlenecks related to AM processing, including imprecision of scanning equipment, (size) limitations, stability and reliability of the print process, absence of machine parameter manipulation, low process automation, low processing speed and low throughput, high equipment and manufacturing cost, post-processing requirements, and the risk of piracy. In addition, the elimination of other bottlenecks is required, for example, ambiguity surrounding regulations, including those related to IP, component certification, liability, warranty, quality assurance, process qualification and certification, as well as testing and inspection.

10. Hybrid designs exist when AM and CM are combined and positioned together in the production chain (I). AM's ability to produce different shaped products with one process means that AM can be used as a flexible manufacturing source, and allows it to be combined with CM (P). This enables products to be developed in a fast and affordable way (e.g. during new product introduction) but also to benefit from economies of scale (O);

2.3.4.4 Deliver propositions

11. In an AM SC design, the digital warehousing of products (I) becomes possible. The additive nature of AM and the availability of a digital file allows physical inventory to be replaced by digital inventory (P), which reduces the need for assets caught-up in inventory and warehousing (O);

12. An AM SC design allows for the digital transportation of products (I). Digital designs allow digital file distribution to replace physical product distribution. This reduces the overall need for transportation and shifts the need for transportation modalities in the SC. Upstream, only basic materials are distributed, while downstream distribution shifts from bulk to fine (P). This reduces transportation costs and increases SC speed (O).

2.3.4.5 Return propositions

13. Closed loop supply chain designs (I) are enabled by the use of universal basic materials. This increases the opportunities for (and scale of) material recycling systems (P). This in turn reduces costs and footprints (O).

14. Closed loop supply chain (I) footprints are also lowered since AM only uses material where needed (P), thus requiring fewer basic materials, and reducing energy emissions, waste, pollution and landfill (O).

15. AM is suited to closed loop supply chain designs (I) as the additive nature of AM requires no product specific equipment, thus allowing for in-situ repair (P). This extends the product life cycle, reduces fix time, improves equipment up-time, and reduces costs, thus making the SC more responsive, cheaper, and closed loop (O);

2.3.4.6 Enable propositions

16. Incorporating a customer communication platform in the SC design (I) allows for collaboration and co-creation between designer and customer(s). This enables fast iterations and leads to high-quality design (P) – improving product quality and reliability of new (innovative) and improved products and services, highly customized products or complex parts (O);

    Bottlenecks include poor and unsecure IT infrastructures; changes may be required and may be expensive.

17. Design-for-AM knowledge (I), along with AM's shape freedom, enables manufacturing of lightweight, high performance and geometrically complex products (P) – empowering SCs to use fewer basic materials and achieve reduced operational costs (O).

    One bottleneck is a lack of AM design knowledge. Other people-related bottlenecks include changes required in the way of thinking of traditional designers; lack of skilled machine operators; workers' resistance to change; lack of management and government support; lack of cost calculation knowledge, lack of customer awareness, and issues related to the customer acceptance of AM.

18. Design-for-AM knowledge (I), along with AM's shape freedom, enable the manufacturing of products in an integrated state (P). This reduces both assembly time and cost (O).

The propositions are visualized in Figure 2.2. The numbers (1 to 18) refer to the related propositions.

2.4 Research agenda and roadmap

This section relates to the second contribution of this article: the proposed research agenda and provision of a roadmap for the roll-out of AM. The research agenda is presented in Table 2.16. It is related to RQ5 and aims to validate and extend the 18 propositions developed in Section 2.3.4.

Next – related to RQ6 – we present a roadmap for the full roll-out of AM once the bottlenecks preventing the full dispersion of AM are solved. As mentioned in Section 2.3.2.3, Rayna and Striukova (2016) consider the diffusion of AM to be a multi-layered innovation process. We focus on the area that will highly impact business: direct digital manufacturing for final products. For these applications, AM is currently mainly used to support CM (Holmström et al., 2017), resulting in incremental improvements only. Bottlenecks serve as thresholds, and prevent the wide diffusion of AM (Durach et al., 2017, Dwivedi et al., 2017), which in turn prevents disruptive game change between SC actors (Fawcett and Waller, 2014, Steenhuis and Pretorius, 2017). First, we summarize the bottlenecks that need to be eliminated. We then relate these thresholds to a roadmap in which AM advances, and increasingly disrupts, supply chain designs.

Stable and repeatable product quality: Elimination of this threshold requires stable and reliable print and scanning processes, and machine parameters to be controlled by skilled operators. The machines need to be able to print good (surface) quality to produce accurate, strong (mechanical properties), durable, consistent and safe products of good quality and proper size. This requires a higher variety of basic materials than are available today; all with good characteristics of guaranteed, standardized, quality. Solving this bottleneck allows for slow-moving, non-critical applications (e.g. class 1 patient-specific medical products).

Product and process certification issues: Elimination of this threshold requires adaptations to regulations, including quality assurance, process certification and qualification, and testing and inspection. Moreover, components certification, warranty, liability and IP rights need to be clear. Eliminating these bottlenecks will enable extension of the AM portfolio to include critical applications, e.g. class 2/3 patient-specific medical products.

Lack of AM design knowledge: Improving AM design knowledge and updating designer attitudes in line with AM will improve product designs, e.g. of lightweight products or products with integrated functions or new applications.

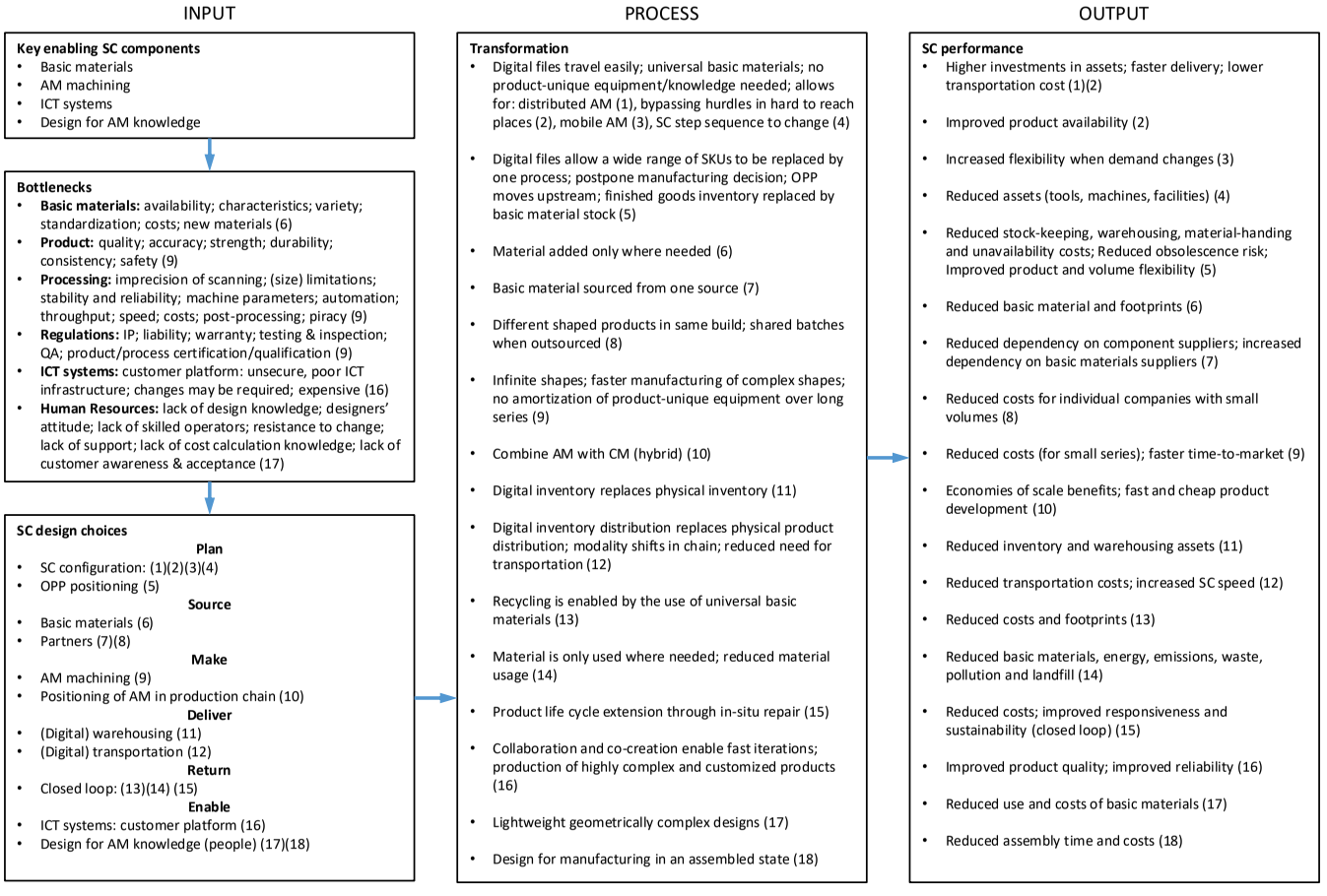


Figure 2.2: Conceptual IPO Model for AM SC Propositions.

Table 2.16: AM SC Research Agenda

Proposition	Research themes
	PLAN
1	The optimal positioning of AM in the SC in terms of cost and responsiveness and the impact of (decreasing) AM machine and basic material costs on these decisions; The cost and responsiveness trade-offs that determine the switch from central to distributed AM.
2	The distribution of raw materials, machines and digital designs in order to improve product availability in hard-to-reach places using AM.
3	The benefits of mobile AM in terms of SC cost and responsiveness; The integration of mobile AM in non-mobile SCs.
4	The reduction of SC steps (disintermediation) when implementing AM in a SC, and the impact of this on assets (tools, machines, facilities) in such SC designs.
5	Decisions related to which CM SKUs can be replaced by AM; The decision about when to switch from CM to AM (for spare parts) and the effects of this on flexibility, product (un)availability and SC cost.
	SOURCE
6	The impact (in terms of volume and footprints) on suppliers of basic material suppliers when CM switches to AM; How to deal with the basic material-related bottlenecks.
7	The effect of the switch from CM to AM on existing supplier relationships, and the management of this transition.
8	The effect of machine and production chamber utilization on SC costs, including the attractiveness of AM (compared to CM) for larger series; The trade-offs between outsourcing to an AM manufacturing platform and in-house AM.
	MAKE
9	The effects of improvements related to the AM processing-bottlenecks (e.g. improved process automation and processing speed) on SC design decisions (e.g. configurations choices) in terms of cost, responsiveness and footprints; The management of databases for highly customized products; How to deal with product-, processing- and regulation-related bottlenecks.
10	The organization and trade-offs (in terms of cost and responsiveness) of hybrid SC designs (e.g. fast-moving CM, and slow and medium-moving spare parts AM; or the use AM for 'bridging' development and early production).
	DELIVER
11	The effects of switching from CM to AM on warehousing and inventory keeping.
12	The effects of implementing AM on upstream and downstream transportation modalities.
	RETURN
13	The reduction of basic material usage when switching from CM to AM initiated by AM's ability to recycle basic materials, including the effects on cost and footprints.
14	The reduction of basic material usage resulting from the fact that, in AM, material is only applied where it is needed, including the effects on emissions, waste, pollution and landfill.
15	The effects of AM's ability to perform in-situ repairs on product life cycle extension, responsiveness, product life cycle costs and footprints.

Table 2.16 continues on next page.

Table 2.16: AM SC Research Agenda *(continued)*

Proposition	Research themes
ENABLE	
16	The requirements for IT systems enabling co-creation platforms; How to deal with IT infrastructure-related bottlenecks.
17	The effects of AM-related product weight reductions on cost over the product life cycle; The determination, building and dispersion of AM design knowledge; How to deal with the people-related bottlenecks.
18	The effects of AM manufacturing in an assembled state on time and cost.

Advanced AM machining: Elimination of this bottleneck requires AM machines to become faster (increasing machine throughput) and able to combine different materials. In addition, the purchase price of machines needs to drop, automation levels need to increase, and post-processing issues must be solved. Moreover, high basic material (sourcing and development) costs need to reduce and more basic materials need to become available. Distributed AM may become financially beneficial as compared to central AM, and mobile AM may be enabled. Following this string of developments, demand volume is expected to rise which will improve production chamber and machine utilization. AM platforms may grow in quantity and size with the related economies-of scope. This will disrupt existing permanent supplier relationships, leading to more adjustable, less asset-demanding supplier relationships (Rogers et al., 2016). Personalization will become affordable to a large share of the population and may evolve into mass-personalization. This will in turn shift the OPP upstream to the design phase (Engineer-to-Order) (Olhager, 2003) for the majority of products. We concur with Mohr and Khan (2015) that, eventually, AM will become quality-, speed- and cost-competitive to CM and disrupt existing business models and supply chains.

Elimination of the above-mentioned thresholds is expected to lead to SC disruption, as visualized in the step-by-step roadmap provided in Figure 2.3. Note that some bottlenecks will never completely disappear (e.g. IP risk). Furthermore, the impact and sequence may differ depending on context, AM technique, and business maturity. Moreover, phases may overlap. In fact, some AM applications already exist today in various phases, including the 'disruptive' phase. For instance, according to Rogers et al. (2016), over 400 AM service providers already exist in Europe. Mainstream mass-personalized AM applications also already exist. Examples include personalized 3D-printed eyewear (materialise, 2019), personalized earphone pieces (uncrate, 2019) and personalized 3D-printed shoes (futurefootwear, 2019).

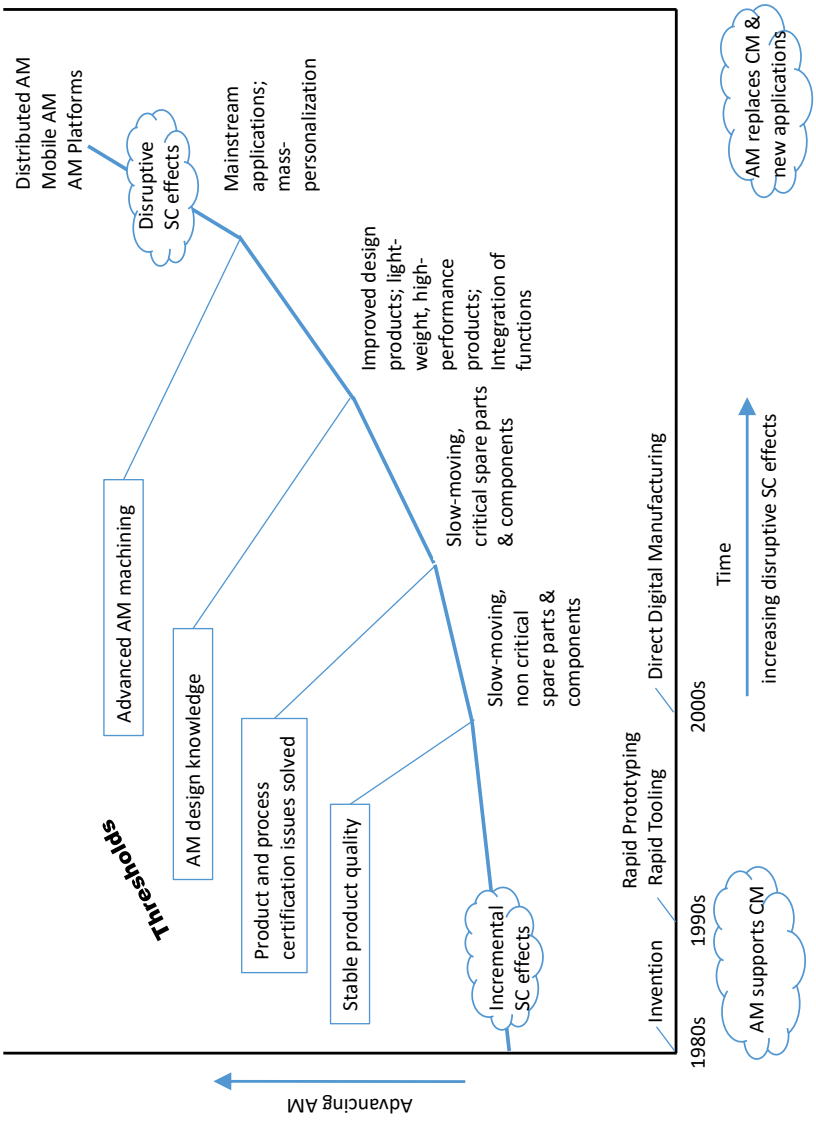


Figure 2.3: Roadmap Illustrating the Impact of Advancing AM and SC Design.

2.5 Conclusion

This article consists of a structured literature review on AM SC design, a conceptual framework, a research agenda and a roadmap for the roll-out of AM. The main objective of this study was to increase knowledge about the disruptive impact that AM has on supply chains design. Six research questions were defined in order to achieve this objective, the answers to which are summarized below:

(RQ1) *In which SC business settings does AM thrive?* AM is mainly used for the manufacture of small, low demand, high-performance components, assemblies, spare parts, prototypes, and tools for many applications in various industries.

(RQ2) *How does AM affect SC design choices and which bottlenecks prevent AM from being used to its full potential?* AM allows the OPP to shift from MtS to MtO and paradoxically to move MtO downstream. Physical inventory changes into digital inventory. Manufacturing can take place close(r) to the point of use. Existing supplier relationships may be disrupted. SC design may become more concise. Moreover, certain SC steps may be removed as a result of a reduced need for production, warehousing, transportation and IT systems, and changes in people's knowledge/jobs. Bottlenecks related to products, materials, processes, regulations and IP still prevent AM from being used to its full potential.

(RQ3) *How can AM influence SC performance outcomes?* AM can reduce SC costs for small series, reduce assets, and increase manufacturing and time-to-market speed. AM may improve product and volume flexibility, reduce carbon footprints and positively influence innovation. Unwanted effects also exist and include e.g. higher costs for larger series, lower product quality, and data transfer security risks.

(RQ4) *How can cause and effect relationships between AM SC design and SC performance outcomes, possibly constrained by bottlenecks, be modelled in a conceptual framework?* From the literature analysis, eighteen propositions were developed and structured according to SCOR. These outline the cause and effect relationships between SC design and SC performance outcomes, detail the transformation process in between, and include the constraining bottlenecks.

(RQ 5) *What does a SC design research agenda designed to further boost SC performance look like?* In order to test the propositions, research themes were included for each of the SC design elements.

(RQ 6) *What does a roadmap for the roll-out of AM for manufacturing purposes look like once the bottlenecks that currently prevent the dispersion of AM are eliminated?* Elimination of bottlenecks that currently present the dispersion of AM will first lead to incremental SC performance improvements. With the advancement of AM machining, we expect

further SC disruptions with AM eventually replacing CM. This development process is presented in a step-by-step roadmap.

We consider academic literature to be somewhat cautious with regard to the potential disruptive impact of AM on supply chains. We agree that AM, depending on the context, currently only causes incremental changes to supply chains, while thresholds prevent a full AM roll-out. However, we concur with Rogers et al. (2017) that SC performance will improve with increasing AM maturity. This means that in the near future, various bottlenecks that currently prevent the wide diffusion of AM are likely to be eliminated. This will trigger a series of yet unknown events that may drastically change the way we deal with supply chains and offer huge potential for improvement. This article contributes to the understanding and modelling of potential SC disruptions and aims to encourage research that helps us to be better prepared for these developments.

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CHAPTER 3



Synthesizing AM SC mechanisms from literature

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Abstract

Additive Manufacturing (AM) is a digital manufacturing technology that enables companies to rethink their supply chain (SC) design. By means of literature synthesis, we build new knowledge about the mechanisms AM induces to improve SC design and performance, as well as the disruptive changes AM can cause. We investigate opportunities to optimize SC design for manufacturing purposes by exploiting the characteristics of AM, e.g., its freedom in terms of shape design and complexity and the absence of a need for object-specific tools. We study the roles of demand, assortment, IT systems, sourcing, manufacturing, knowledge, warehousing, and transportation, and explore the effects and tradeoffs on various SC performance outcomes, including cost, assets, and responsiveness. The contribution of this article is twofold. First, through literature synthesis, we construct six AM SC mechanisms that can be used in SC design to achieve desired SC outcomes for AM production applications in certain (business) contexts. Second, we identify the disruptive 'game-changing' effects of AM for SC stakeholders. This knowledge can be used by other researchers to develop further research. Moreover, general and logistics managers can use the results to fully exploit the potential of AM for designing much improved supply chains. Innovators and policy makers can use the results to understand the potential game-changing consequences of AM.

3.1 Introduction

We live in dynamic times. Swab [1]—founder and executive chairman of the World Economic Forum—argues that the world is at the frontier of the 4th Industrial Revolution. Technology—e.g., mobile supercomputing, artificial intelligence, robots, and autonomous vehicles—changes at an ever-increasing pace, and transforms societies. Over the last few decades, these, and other factors—such as rapid growth of the world population, customer awareness, sustainability issues, and globalization—have all created new performance challenges for supply chains.

A supply chain (SC) is a set of three or more organizations or individuals directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to the customer and vice versa. Creating customer value, lowering costs, increasing responsiveness, co-creation, managing demand variations—and ultimately creating a competitive advantage—are the overriding goals of SC management [2]. SC design is a strategic issue for any company [3], and can be defined as a set of decisions regarding structure, partners, locations, capacities, and systems for SC management [4]. We suspect that, due to these new challenges, traditional SC concepts can no longer support managing the trade-offs between supply chain objectives. By applying new technologies, multiple objectives—in this article called SC outcomes [5]—may be achieved concurrently (e.g., the triple bottom line). One of new technologies is Additive Manufacturing (AM), also known as 3-D printing, Rapid Prototyping (RP), Rapid Tooling (RT), Rapid Manufacturing (RM), or (Direct) Digital Manufacturing [6,7]. What these makes AM unique is that material is added layer-by-layer, contrary to subtractive, traditional or tool-based manufacturing, where the starting point is a solid piece of material and pieces of material are subsequently removed. According to Rayna and Striukova [8], the adoption of AM for prototyping and tooling applications has reached a stage of maturity, contrary to AM applications for (regular) manufacturing and 'at home' fabrication.

Current academic literature is unclear about the implications of AM for supply chains. Within the management literature, AM is viewed as being disruptive to existing business models and supply chains [9–12], while there is more ambiguity in the academic literature. Some authors consider AM to be a useful production technique for particular products [13,14], while Steenhuis and Pretorius [15] suggest that AM will result in incremental as well as disruptive innovation. Incremental innovation may occur in situations where AM replaces or complements existing traditional manufacturing, while disruptive 'game-changing' effects [16] may occur when, for instance, manufacturing moves from central factories to individual households.

Research on the implications of AM on SC design is still in its infancy, and Waller and Fawcett [17] have encouraged researchers to publish studies which address this par-

ticular gap in the literature. Moreover, Holmström, Holweg, Khajavi, and Partanen [6] have identified 'SC structure' as key to their research agenda. In this article, we focus on the potential of AM for designing vastly improved supply chains and, in doing so, intend to fill this knowledge gap.

In this article, we analyze how the unique characteristics of AM influence SC design, SC outcomes and SC mechanisms—and ultimately disrupt the game of the SC players. In particular, we focus on the manufacturing applications of AM. More specifically, we explore SC mechanisms, which we define as the link between SC design elements and SC outcomes. SC mechanisms determine how management decisions influence the performance of supply chains. Examples include economies of scale, customization, and postponement. The unique characteristics of AM in supply chains may induce mechanisms that enable adjusted supply chains design, improving SC performance outcomes and changing the game of (disrupting) the position of SC stakeholders. In this article, we show that AM can alter these mechanisms significantly. For instance, AM's freedom in shape design may take 'customization' to the next level. Using a digital design and a customer co-creation platform allows customers to become (co-) developers, and makes it possible to provide affordable personalized healthcare products to a larger share of the population [18–20]. AM may also change 'postponement'. Digital inventory may replace physical inventory and products may be produced on-demand, enabling in-situ and on-demand manufacturing in difficult-to-reach locations. Product availability and responsiveness may increase, and costs may decrease. Some existing SC participants may become redundant, e.g., customs and transportation [14,21,22].

We used the so-called CIMO logic to carry out a thorough and fine-grained literature synthesis in order to cumulate existing knowledge and generate new knowledge about AM SC mechanisms [23,24]. This systematic review has allowed us to construct six AM SC mechanisms—and is the first contribution of this article. We also explore the conceptual relationships between SC design and outcomes in various contexts, and explain the differences between these new mechanisms and more 'traditional' SC mechanisms. Our second contribution is determining how these improved SC outcomes can disruptively change the game of SC stakeholders. The method we used for literature synthesis may serve as an example for other researchers who seek to generate new knowledge about SC mechanisms and disruptions caused by these new technologies. Moreover, managers can use the results of this literature synthesis to exploit the potential of AM when designing vastly improved supply chains, while policy makers and innovators can use the results to improve understanding of the potentially game-changing effects of AM.

3.2 Contemporary Developments in SC Design

To set the scene, we first discuss contemporary developments in supply chain design. SC management overlaps with many other (management) fields, e.g., human resource management and information technology, and has porous and diffuse boundaries. To standardize definitions and enable benchmarking of processes and performances, the APICS organization developed the Supply Chain Operating Reference (SCOR) model [25]. This model uses the following categories—plan, source, make, deliver, return and enable—which together describe the steps (and decisions) involved in SC design. SC designs influence the 'SC outcomes' in terms of performance, and further elaboration on this topic will follow in Section 3.3.1. According to Fawcett and Waller [16], the SC design is of strategic importance to ensure a firm's competitive position. SC decision makers must determine the right partners, roles, and relationships, in order to build a winning organization. SC designs are influenced by—and have to deal with—contemporary developments. The rise of information technology (IT) is a major disrupter of SCs. Examples include big data and predictive analytics, AM, autonomous vehicles and borderless SCs [16]. Next, we discuss disrupters and the impact on SC design in more detail.

As a consequence of the rise of the internet in the last few decades, traditional shops have largely been replaced by web shops. Several steps in the SC have been removed causing 'disintermediation' [26] and changes in the roles, knowledge and skills of people in the chain (e.g., from sales person to warehouse associate). Changes also occur in transportation modalities (e.g., truck deliveries to shops being replaced with at home delivery with vans), and in facilities (e.g., shops being replaced with distribution centers). Some tangible products have been turned into intangible products, for example video tapes, DVDs, vinyl, CD's, and books sold or rented out in shops have been converted into streaming platforms or e-books, thus removing and changing SC steps. Other tangible products can now be accompanied by (digital) service products—a process called 'servitization', which changes supplier and customer relations [27].

The quest for digitization, however, continues. A 'digital SC' is defined as 'a smart, value driven process, generating business value with novel and technological and analytical processes' and including e.g., augmented reality, cloud computing, sensor technology and internet of things [28]. Moreover, automation and robotization reduce the dependency on human resources and can potentially increase SC speed and reduce SC cost [29]. The development of blockchain technology is still immature but can potentially eliminate administrative and control tasks, thereby simplifying SC designs (again disintermediation) and reducing cost [30]. Internet technology-based platforms arise in line with 'the platform economy' [31]. Production capacity or transportation capacity can be shared by multiple customers. For example, the platforms Uber Freight

and Pamyra enable sharing transportation capacity, which improves resource utilization, and reduces cost and footprints.

Customization is another trend. In the early days of mass-manufacturing, the amount of choices a customer could make were limited: According to Henry Ford, you could order any color T-Ford you like—as long as it was black. However, due to rising competition and customer expectations, the customer order decoupling point (CODP) has moved upstream, and the amount of options for customers has become unlimited, allowing for the creation of mass-customization. Mass-customization is a marketing and production concept used to create personalized products based on product modularity. It blends adaptability (the ability to produce customer specific products) with the low per unit cost of mass-manufacturing [32]. Postponement delays the production decision until the customer order is received [33,34]. Economies-of-scale requires that expensive (specific) tools are amortized over long series, but mass-production has limited flexibility and requires high inventories [35]. Lean manufacturing [36] and Single-Minute Exchange of Die [35] overcome some of these disadvantages and hence enable mass customization and personalization. Internet supported platforms allow customers to become increasingly involved in the design process and to 'co-create' [17] and take over tasks that used to be designated to designers and developers at companies.

The final trend we discuss is the sustainability trend. SC design meant to 'close the loop' focuses on the 'return' element of the SCOR model, and aims to reduce footprints, pollution, and resource scarcity [37]. This can result in benefits over the product lifecycle such as the reduced fuel consumption of light-weight products for, e.g., aerospace and car applications. The Paris climate treaty of 2015 has boosted awareness of the effects of (carbon) footprints on climate change. Sustainable supply chain design focuses on balancing the triple bottom line of profit, people, and planet, and addresses issues such as corporate social responsibility, e.g., child labor [38].

3.3 Methodology

This article describes the first phase of a larger research project—which includes empirical research—on the impact of AM on SC design. Conducting a thorough literature review is considered to be a good way of identifying the knowledge previously created. Systematic literature review (SLR) approaches have been recommended as they can find evidence for the clarity, validity, and auditability of the research—or, in other words, show that the findings are grounded [39]. According to Tranfield et al. [40], SLR can help to build a body of knowledge and provide a reliable basis for decision making. Pawson [41] has advocated taking literature reviews one step further by not merely summing-up existing literature, but rather synthesizing existing studies in order to enhance the generalizability of qualitative research. Since little theoretical knowledge exists in our field, our goal

was to synthesize existing studies and develop new knowledge for designing supply chains using AM, therefore contributing to improved SC performance. We followed the general guidelines on SLRs provided by Booth, Sutton, and Papaioannou [39], and complemented these with the SCM specific guidelines provided by Durach et al. [42], using their recommended sixth step approach. Sections 3.3.1 through 3.3.6 explain these steps in more detail. Note that the fourth step (literature analysis and synthesis, Section 3.3.5) comprises more than usual, since we accumulated knowledge in order to create new knowledge by constructing six AM SC mechanisms, which are further explained in Section 3.4.2. The new knowledge we built (the AM SC mechanisms) from theory can be described as propositions that need to be verified using empirical research. However, this verification is not within the scope of the present article.

3.3.1 Initial Theoretical Framework and Question Formulation

Prior to defining the research questions, Durach, Kembro and Wieland [42] recommend that an initial theoretical framework is developed, specifying the scope of the unit of analysis. Our analysis is primarily about how SC designs, including the use of AM, influence SC outcomes. It identifies the two major theoretical components: SC design and SC outcomes. In order to build the theoretical framework, we used the CIMO framework of Design Science Research (DSR) [24], as suggested by Booth, Sutton, and Papaioannou on p. 87 in Reference [39]. In line with Mulder [43], and Tanskanen et al. [44], we used DSR's CIMO reasoning chains as a framework for a systematic review of the selected articles.

The logic behind this structure is that, in order to achieve the desired Outcome (O) in a certain Context (C), Intervention (I) might be effective, and needs to be validated in the field [45]. Pawson and Tilley [46] added the issue of causality by conceptualizing the Mechanism (M) that is activated by the intervention and delivers the outcome. Together, this creates the CIMO structure [23,47,48]. In our case, in a particular context (C), an SC design, including AM (I), leads, via certain mechanisms (M), to certain SC outcomes (O). We will now explain these elements in more detail. Context: This describes the business environment in which the particular supply chain operates. Intervention: We defined the design of the SC, including the application of AM, as the intervention, and used the SCOR (Supply Chain Operations Reference) model elements plan, source, make, deliver return and enable [25] as an overall structure and integrated the SC design involves choices related to capacity and position of manufacturing and warehousing facilities, assortment, sourcing, transportation modalities, and information systems [4]. Mechanism: In DSR's CIMO logic, mechanisms connect interventions with outcomes, in a given context [24]. In line with this, we define AM SC mechanisms in the following way:

> *"An AM SC mechanism links the SC design elements (including AM) with the SC outcomes in a given context"*

SC mechanisms determine how management interventions can influence the performance of supply chains. According to van Aken, Chandrasekaran, and Halman [24], there is no straightforward way to determine these mechanisms. We chose to cluster the determined CIMO reasoning chains and in a creative, iterative process, assigned AM SC mechanisms. The mechanisms we identified—resulting from our literature synthesis—constitute one of the two main contributions of this article. We present them in Section 3.4 and compare them to equivalent SC mechanisms that existed prior to AM, e.g., mass-customization and postponement. Outcome: We define 'outcome' as the SC performance outcomes. The SCOR model [25] defines five supply chain outcomes: cost, assets, responsiveness, reliability, and flexibility [49]. According to Melnyk, Davis, Spekman, and Sandor [5], the supply chains of tomorrow must deliver varying degrees of six blended outcomes—in this scenario, security, sustainability, and innovation are added to the traditional outcomes of cost and responsiveness. We used the outcomes of both sources in this article. In line with Holmström et al. [50], we also checked for other, unintended consequences (side effects). These unintended outcomes may, for example, include cost increases for large series, high energy costs, or a larger carbon footprint.

Together, this results in our initial theoretical framework, as presented in Figure 3.1.

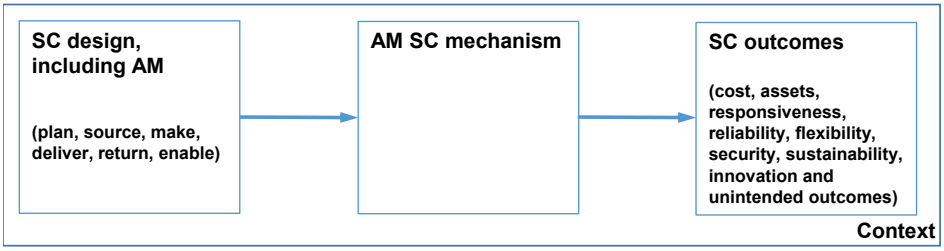


Figure 3.1: Initial theoretical framework.

The main objective of this study was to investigate how AM can improve SC designs for manufacturing applications. More specifically, we wanted to develop mechanisms to explain the relationship between AM SC design and outcomes. To this end, our research questions were:

1. In which contexts are AM supply chains used, how are they designed, and how do they perform?
2. What AM SC mechanisms for manufacturing applications can be constructed and what are the conceptual relationships between intervention (I) and outcomes (O) in various contexts (C)?
3. What are the disrupting effects of using AM supply chains for the SC actors?
4. How are AM SC mechanisms related to 'traditional' SC mechanisms?

3.3.2 Identifying the Characteristics of the Studies

In this phase, the inclusion and exclusion criteria are defined by assessing the contribution to the theoretical framework [42]. In order to guarantee high quality information, we only included scholarly peer reviewed articles and therefore excluded books and grey literature. While acknowledging that this is an innovative field that is developing at a fast pace, and academic literature often lags behind (due to the relatively long throughput time), we felt that only including high quality sources was preferable to including other (grey) sources, despite the fact that they may have provided some valuable insights. We did not apply time-restriction parameters, nor did we limit ourselves to articles in predetermined research fields, or exclude certain types of articles (e.g., empirical). For practical reasons, only sources written in the English language were used.

To synthesize the potentially relevant literature sample (discussed in Section 3.3.4), we determined that the selected articles should contain one or more of the context, intervention, or outcome elements, as defined in the theoretical framework presented in Section 3.3.1.

3.3.3 Retrieving Samples of Potentially Relevant Literature

In this step, potentially interesting literature is obtained through rigorous searches. We first identified the right key words and considered the breadth of the SCM field to determine the synonyms. In order to reduce retrieval bias [42], the researchers discussed the search terms and iteratively improved them during initial searches. This resulted in the key words presented in Table 3.1. The selected words were connected via AND/OR Boolean logic in order to find suitable articles. While recommended, we did not apply quality parameters (e.g., only include highly cited articles) in order to reduce publication bias [42].

Table 3.1: Key words

Supply Chain Design	Additive Manufacturing
Supply Chain OR Supply Network OR Logistic OR Value Chain OR Network Design	Additive Manufacturing (AM) OR 3D Printing OR 3 Dimensional Printing (3DP) OR Rapid Manufacturing OR Rapid Prototyping OR Stereo Lithography OR DDM OR Digital Manufacturing OR Solid Free-form OR Layer Manufacturing OR Rapid Casting (RC) OR Rapid Tooling (RT) OR Material Deposit Manufacturing OR Material Addition Manufacturing OR Additive Layer Manufacturing

Using the search terms and characteristics, we performed several searches in the period between October 2016 and January 2018. During that period, the list of articles was updated several times in order to include the latest developments. We used online university software, which provided access to various databases including Emerald, Science Direct, Web of Science, and Google Scholar. This resulted in 503 unique articles and conference papers which were transferred to Endnote. The oldest article found dates from 1993.

3.3.4 Synthesizing Samples

The abstracts of the 503 articles were reviewed on the basis of whether they included the context, intervention, and outcome elements of our theoretical framework (Figure 3.1). In case of doubt, the full content of the article was scanned for relevance. This led to the exclusion of 456 articles. We found that our search terms also directed us to non-relevant articles. These articles were of a technical nature, for example, they included a discussion only of AM technology, or a technical discussion of AM print materials, or digital modelling (not AM-related) or SC modelling (e.g., for simulation, but not AM-related). To prevent inclusion criteria bias [42], and in order to be transparent, the reasons for exclusion were registered in a file. The remaining 47 articles were read in full. While reading the articles, we checked the citations (snowballing), a useful method for building up a good body of literature and identifying studies that may have been missed via bibliographical searches on p. 121 in Reference [39]. This resulted in 13 additional articles being added to the full article review. Moreover, during the peer review process, our attention was drawn to one additional article which we also added. The absence of these 14 articles in the original searches can be explained by the fact that SCM is a broad and permeable science [42] and the authors of these articles did not consider the articles to be SCM relevant (although they did in fact prove to be relevant). Due to practical constraints, we did not involve multiple researchers and a blind selection process, although this has been recommended by Durach, Kembro, and Wieland [42] as a way of preventing selector bias.

In the articles that we fully reviewed, the relevant SC information was often missing, hidden or vague, which is in line with the complex issues that arise in organization and management [23]. The articles originate from 27 different journals, encompassing a broad range of categories (Table 3.2), which reduces the chance of missing crucial elements. It is important to note that, although all our selected articles have been peer reviewed, most are based on experiential knowledge, and while this can provide us with valuable insights, only relatively few are based on rigorous empirical evidence.

Table 3.2: Journal categories

Journal Categories	Number of Articles
Manufacturing/Production/Technology	27
SC/Logistics/Operations Management	12
Information Systems	5
Business/Economics	5
Social/Ethics	4
Ecology/Energy	4
Materials/Engineering	2
Unknown	2
Total	**61**

3.3.5 Analyzing and Synthesizing the Results

Research synthesis (or research integration) refers to finding similarities in related research, while at the same time taking differences into account, a process which potentially leads to generalization [51]. This step itself consists of two parts. First, a coding scheme is developed based on the initial theoretical framework. The second part then involves analyzing and integrating the results.

In line with this, and based on our initial theoretical framework, we developed a two-step coding scheme. The main codes were based on theory and are listed in column 1 of Appendix 3.1. We allowed for open coding. The detailed codes that emerged during analysis of the articles are listed in column 2 of Table A3.1 in Appendix 3.1.

For the main codes related to 'AM SC context', we differentiated between industry and product type [52], sales channel [53], product life cycle phase [54,55], and demand characteristics [56]. We also included barriers to AM implementation, which may impede the far-reaching diffusion of AM [57].

For the main codes related to 'SC design intervention', we used the SCOR elements (plan, source, make, deliver, return, enable). In the SCOR element 'plan', we included stock-keeping-unit (SKU) choices and other SC planning related interventions, e.g., changing order of SC steps or elimination of SC steps. In 'source' we included the sourcing partner choices. In 'make', we included the Customer Order Decoupling Point (CODP) [58,59], the positioning of AM in the chain (SC configuration) and the positioning of AM machines in the operation. In 'deliver', we included the impact and choices related to inventory keeping, warehouse and warehouse equipment, as well as choices related to transportation (modalities). In 'return', we included returns management [37], with disassembly, recycling, assets' lifecycle, waste materials and pollution, and, finally, in 'enable' we included choices related to IT systems and the impact on people working in

the chain. Note that the main codes (overall categories) were developed from theory, while the aforementioned detailed codes (subcategories) were developed in an iterative process while reviewing the literature. For the main codes related to 'SC outcomes' we used the categories as defined in the theoretical framework (Figure 1). We did not use coding for the 'mechanism' since this is a result of our synthesis (this will be further explained in Section 3.4.2). While we coded the literature to the best of our abilities, for practical reasons we were not able to use multiple independent coders to prevent within-study bias, as recommended by Durach, Kembro and Wieland [42].

While analyzing the 61 articles and developing the coding scheme, the existing published research was synthesized into 'means to end statements' or 'CIMO reasoning chains' [45] with the aim of determining the main mechanisms that turn interventions into outcomes. The mechanisms we developed are explained in Section 3.4.2. Again, due to practical constraints, we were unable to conduct parallel and blind synthesis involving multiple researchers, as recommended by Durach, Kembro and Wieland [42] as a way of preventing expectancy bias.

3.3.6 Reporting the Results

The results are reported in Section 3.4.

3.4 Results

We present the information in the following sections. In Section 3.4.1 and Appendix 3.1, we present the results of the literature analysis. In Section 3.4.2, we outline the results of the literature synthesis, by constructing the AM SC mechanisms and the conceptual relationships between SC design and SC outcomes.

3.4.1 Descriptive Results

This section refers to Research Question 1. Since this contribution relates to the literature synthesis (Section 3.4.2), we merely highlight the most frequently mentioned findings related to the context (C), intervention (I) and SC outcomes (O) of the literature study, while Table A3.1 in the Appendix 3.1 contains the complete findings. The Mechanisms (M) are presented in Section 3.4.2.

AM was first adopted for (rapid) prototyping and (rapid) tooling in the 1990s, and by now the related supply chains are mature. The next phase—rapid manufacturing or (direct) digital manufacturing—started in the late 2000s when costs lowered and manufacturing quality improved sufficiently. The last phase—home fabrication by consumers—started in the early 2010s and is in a very early phase of development [8].

The remainder of this discussion focuses on the RM or DDM phase. Our findings show that AM is used in many industries and for many different applications e.g., aeronautics, medical applications, (car) manufacturing, consumer products and construction. Frequently mentioned applications include spare parts, components and assemblies for both manufacturing and maintenance purposes. In the current state of development, AM is often used to cope with fluctuations in demand and for (very) low demand, or for the production of single units. For manufacturing purposes, many barriers still exist related to quality, materials, processing, (lack of) knowledge, a lack of clarity about IP, and a lack of legislation/regulation.

The use of AM may make supply chains shorter and simpler, and the order of steps may change. Finished goods may be replaced with raw materials, and digital inventories may replace a large assortment of physical inventories. Fewer machines, buildings, and tools may be required. Online platforms may be required for the (co-) creation, storage and retaining of digital files. There may be reduced demand for raw materials which can be sourced from the same (local) source. This reduces dependency on component suppliers, and increases dependency on material suppliers. Desired scale-economies may initiate outsourcing to AM service providers. AM can either replace or complement traditional-manufacturing, the CODP may shift, and central, distributed and mobile SC configurations may exist. People's roles may change and new knowledge may be needed. Transport modalities may also require change and there may be a reduced need for warehousing.

AM mainly reduces SC costs by reducing inventory, raw material, production, assembly, transportation and operational costs. Moreover, there may be a reduced need for assets, and, for small series, responsiveness may improve. Quality, reliability, flexibility, sustainability and innovativeness may also improve. Unintended outcomes may also occur, e.g., data transfer security risks may arise as a result of knowledge leaks. For larger series, product costs may be higher and product availability may be slower. According to the analysis, the key SC decisions for designing AM SCs concern:

- AM equipment, including decisions about the positioning of machine(s) in the SC; AM allows unlimited freedom of (shape) design in the manufacturing of light-weight products with integrated functions, requiring no object specific tools (to be amortized over long series). It also allows production of different shaped products in the same production run;
- Supply of raw materials products are produced from the same source material (e.g., powder). Material is (relatively) easily transported to (local) AM production;
- Design for AM knowledge are required to realize the full potential of specific digital designs;
- Customer platforms enabling ordering and/or co-creation between designer/customer and manufacturers;
- System for the storage of designs enabling design reuse and/or adaption.

The above-mentioned SC decisions are key for constructing the AM SC mechanisms outlined in the next section.

3.4.2 Constructing AM SC Mechanisms

This section refers to Research Question 2, and relates to the first contribution of this article. According to CIMO, interventions lead to outcomes induced by mechanisms. In this section, we outline six AM SC mechanisms that were constructed as new theory from our literature synthesis. The related figures show the conceptual relationships between the SC design interventions and outcomes for each mechanism.

3.4.2.1 Co-Customization Mechanism

The co-customization mechanism originates in the mass-customization mechanism in traditional manufacturing. Co-customization (Figure 3.2) goes one step beyond. It is enabled by an intervention of (a) AM's unlimited shape freedom in terms of shape design, (b) system storing designs to share and re-use [60], and (c) a customer platform enabling co-creation [8,17] between designer (customer or representative) and manufacturer. It personalizes output by means of offering unique products and customer involvement and improves quality through iterations. It seamlessly serves the needs of the customer with further-improved or new product innovations, even for products that were previously impossible to make [61]. AM enables the production of products with high customization and high complexity at low or zero added cost [62]. Design iterations enable improvement updates after every single unit [6]. The classic distinction between the product lifecycle phases 'design' and 'manufacturing' becomes permeable; the phases are integrated. In fact, every manufactured product is potentially a new prototype where what has been learnt from previous designs can be integrated into future designs.

Applications of this mechanism are found in customized healthcare products [18–20,62–64].

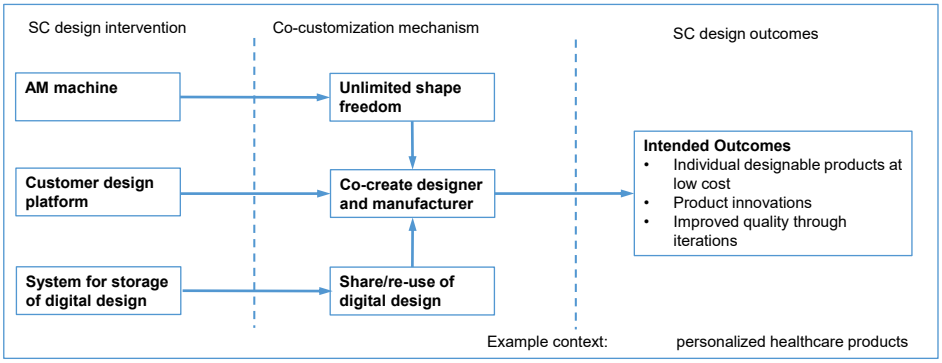


Figure 3.2: Co-customization mechanism.

3.4.2.2 In-Situ & on-Demand Mechanism

The in-situ & on-demand mechanism uses elements of the traditional 'postponement' mechanism but offers more options. When making the change from traditional manufacturing to AM, Make-to-Stock (MtS) may become redundant, and Make-to-Order (MtO) or Engineer-to-Order (EtO) may become economically feasible. In this case, the CODP moves upstream, however, due to the elimination of SC steps, far less so than in traditional manufacturing. Effectively, for MtO and EtO, the CODP shifts downstream towards the customer, while for MtS it remains the same. In other words, CODPs now almost concur, whereas they were miles apart in the past.

The in-situ and on-demand mechanism (Figure 3.3) is enabled by an intervention of (a) AM requiring no object specific tools and a shorter SC with reduced steps, (b) systems to create (scan) or store designs allowing design-sharing and reuse, and (c) local supply of one source of raw materials. This allows manufacturing in distributed locations [65] near or on-site at the customer location, from one source of raw material, reducing transportation requirements and improving order lead-time and product availability.

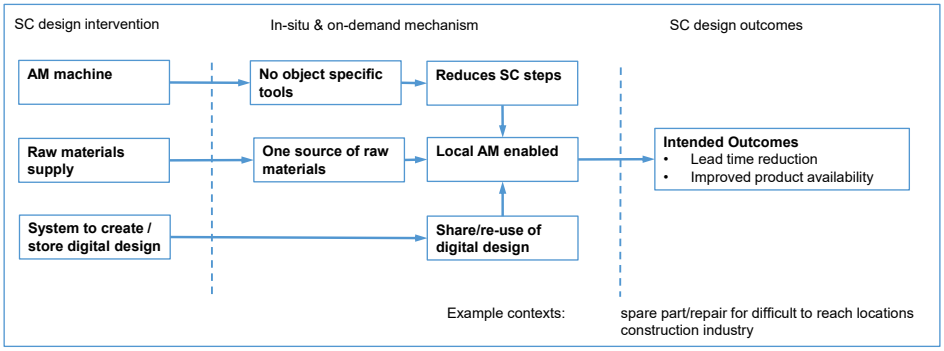


Figure 3.3: In-situ & on-demand mechanism.

Applications of this mechanism have been reported for difficult-to-reach locations. De la Torre, Espinosa, and Domínguez [21] reported that AM of truck spare parts for humanitarian aid can improve truck availability as a result of bypassing customs, and reduce potential theft, bribery and transportation issues. To obtain the digital file, scanning or cooperation with the truck manufacturer may be required. Ford and Despeisse [66] have mentioned the in-situ repair of turbine blades, and Kothman and Faber [67] have described the on-site production of parts allowing for lighter designs and reducing SC steps. Moore et al. [68] have described on-demand AM of coronary stents in operating room—potentially reducing the supply chain lead-time. Finally, Ryan et al. [69] have described mobile AM for spare parts production in difficult to reach locations and for the construction industry.

3.4.2.3 Shared-Economies Mechanism

Economies-of-scale is the traditional mass-manufacturing equivalent of our shared-economies mechanism. However, AM takes economies-of-scale to another level. When designing an operations strategy, process choices [70] are required. AM offers new options, since standardized processes can flexibly produce specialized products. Unique products—which, according to the product-process matrix of Hayes and Wheelwright [71], are traditionally produced in a jumbled flow (job shop)—can now be produced in a disconnected line (batches), traditionally reserved for small series of the same products.

The shared-economies mechanism (Figure 3.4) is enabled by an intervention of (a) AM with its unlimited freedom in shape design allowing various unique products to share one batch, (b) a customer platform allowing consolidation of orders, and the support of (c) a system that stores digital files. This leads to faster production and cost reductions for low demand products.

The absence of product specific tools makes amortization of expensive tools over long series of identical products unnecessary [6,61,72]. This is called the 'economies-of-one' concept [13,16], and can either coexist with economies-of-scale [73], or make it irrelevant [74]. Since the AM build chamber should be utilized efficiently, demand from various customers can be pooled and outsourced to an AM service provider who can have economies-of-scope in equipment and material purchasing, labor, and knowledge [13,75].

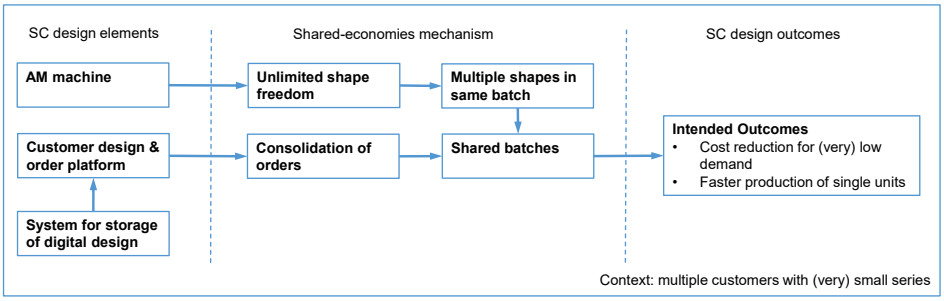


Figure 3.4: Shared-economies mechanism.

3.4.2.4 Digitized Stock Mechanism

AM enhances the possibilities of traditional postponement [33,34]. An AM SC allows digital inventory to replace physical inventory [14,22,62,76–78], transferring the differentiation decision physically closer to the point-of-use (hence downstream), but paradoxically, the CODP shifts upstream from MtS to MtO process wise.

The digitized stock mechanism (Figure 3.5) is enabled by an intervention of (a) AM requiring no object specific tools, (b) raw materials supplied from the same source in (c) a system storing digital designs to share/reuse. This allows differentiation at the latest moment and consequently results in replacement of a range of stock keeping units [14,76]. Moreover, it improves parts availability and reduces the need for inventory keeping.

Applications of this mechanism include the production of spare parts [79,80] with very low demand or parts shortage [72,81]. Pérès and Noyes [14] have mentioned causes like destructed tools and company liquidation and Sasson and Johnson [82] have compared AM slow moving spare parts to 'the long tail'. Note that MtS is still possible with AM but that MtO and EtO become serious alternatives, as discussed in Section 3.4.2.2.

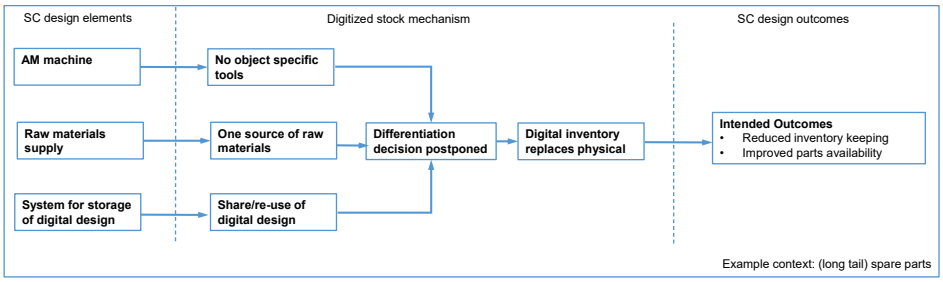


Figure 3.5: Digitized stock mechanism.

3.4.2.5 Buy-to-Fly Spin-offs Mechanism

The 'buy-to-fly ratio' is the weight of raw material bought, versus the material weight actually used in the part [73,83]. It is not a new concept, but AM enhances its potential and creates spin-offs.

The buy-to-fly spin-offs mechanism (Figure 3.6) is enabled by an intervention of (a) AM with its unlimited freedom in shape design, (b) specific AM design knowledge resulting in (c) a digital design. This combination allows production of light, complex and strong products—where less material is required during production, improving the 'buy-to-fly ratio'. At the same time, lightweight products create spin-offs during the product's life-cycle by reducing fuel consumption, carbon footprint and cost [73,83].

Typical applications of this mechanism are found in lightweight and complex structures for low-demand, high-performance components and assemblies in the aeronautics industry [66,75,84].

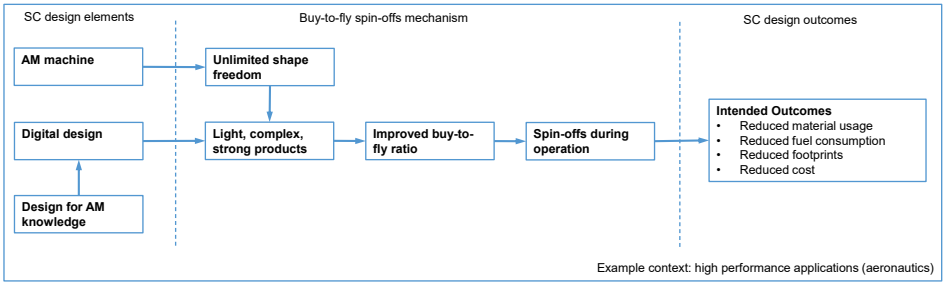


Figure 3.6: Buy-to-fly spin-offs mechanism.

3.4.2.6 Functionality-Integration Mechanism

Related to this mechanism is the SC disintermediation mechanism in traditional manufacturing, which constitutes the removal of steps in the SC and is often related to online transactions and e-commerce [26].

The functionality-integration mechanism (Figure 3.7) is enabled by an intervention of (a) AM with its unlimited freedom in shape design allowing integration of functions during the production process, (b) specific AM design knowledge resulting in (c) a digital design. The combination of these SC design elements allows for the production of products with integrated functionalities and the elimination of certain SC steps. In fact, production and assembly tasks reduce, resulting in increased SC speed and reduced costs.

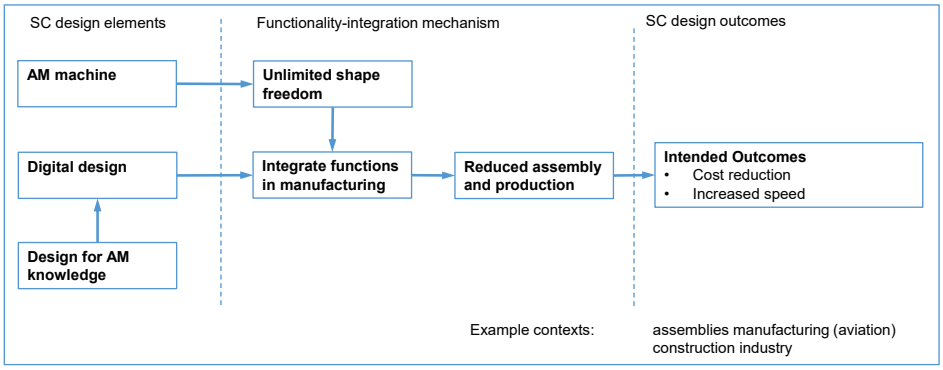


Figure 3.7: Functionality-integration mechanism.

Glasschroeder et al. [85] made a distinction between integration of mechanical functions (e.g., assembled parts inside), thermodynamic functions (e.g., integrated heating channels) and electrical functions (e.g., integrated conductive materials). Examples of this mechanism can be found in the integration of mechanical functions in assemblies

[78,86] in the aviation industry [75], and in the integration of thermodynamic functions (cooling channels) in the construction industry [67].

3.4.3 The Game-Changing Effects of AM SC Design

In light of the 4th industrial revolution, managing supply chains and adapting their designs is a major challenge in a rapidly-changing world. This section answers Research Question 3, and relates to the second contribution of this article by identifying the game-changing effects of SC designs using AM, where a 'game-changer' disruptively changes the game between actors [16]. In line with Steenhuis and Pretorius [15], who have suggested that AM causes incremental innovation in one context, while being disruptive in another, we define the game-changing effects for the stakeholders per context and per mechanism, and underline the affected stakeholders.

In an AM SC 'co-creation', customers are actively involved in the design process—allowing them to become 'prosumers' [66,73,76]. Manufacturing may move from centralized factories to individual households, customers become developers, and manufacturers become entrepreneurs in the 'maker-movement' [16].

Once technological and regulatory issues have been solved, the impact of using this technology for medical device manufacturers and their suppliers may be extreme. Moore, O'Sullivan and Verdecchia [68] reported a test case where in-operating room AM of stents can shrink the SC lead-time from 150 days to 20 min. Individual companies lack the scale economies to efficiently utilize the AM equipment, and may outsource to regional printing centers who consolidate order volume from various customers [13,75]. Rogers et al. [87] identified 404 of these 'supercenters' already in existence in Europe, serving multiple markets. Flexible and less capital-intensive relationships may replace fixed relationships with machine suppliers.

In difficult-to-reach locations, due to factors related to poor infrastructure, geography, danger, customs, or bribery [14,21,22,62,69], manufacturing interruption may be expensive or late delivery may have negative consequences [88]. AM may enable local and on-demand AM of e.g., spare parts, which allows the bypassing of e.g., customs and transportation. Moreover, better local product availability may improve living standards in developing countries, exerting an influence on society as a whole. AM may be used for the manufacturing of surgical tools [19], for improving surgical procedures, reducing cost and improving patient well-being (relevant for hospitals and insurance companies). In-situ repair of equipment, e.g., turbine blades [66] may extend product life-cycle, improving equipment up-time, reducing cost, improving footprints, and disrupting the roles of manufacturers, repair-agents, customers, and society as a whole.

AM's ability to produce lightweight, strong and complex structures supports the manufacturing of lightweight components, for e.g., aeronautics applications [66,75,84],

Table 3.3: CIMO per mechanism and disruptive effects on SC stakeholders

	Context	SC Intervention	Mechanism	Desired SC Outcomes	Disruptive Effect on Stakeholders
I	• Personalized medical devices	• AM machine • System for digital design • Co-creation platform	• Co-customization	• Highly customized products • Improved quality through iterative development • Improvement updates after every product produced • Improved responsiveness and reliability at lower cost	• Customers: become developers, actively involved in design process • Producers: become entrepreneurs • When AM reaches maturity: dramatic changes in competitive position • Society: affordable healthcare available for larger share of population
II	• Spare parts/ repair • Difficult to reach locations • Construction industry	• Local AM machine • Local supply of raw materials • System for creation and storage of digital design	• In-situ & on-demand	• Lower cost of transportation, raw materials, and finished goods • Improved responsiveness • Improved product availability	• Customers: Increased customer service (healthcare) level • Customs: role changes due to potential bypassing • Society: reduced theft, bribery • Suppliers: reduced need for transportation • Manufacturers and repair agents: extended product life-cycle • SC players: elimination due to elimination of SC steps
III	• Multiple customers with (very) small series	• AM Supply Platforms • AM machine • System for digital designs • Customer platform	• Shared-economies	• Cost reductions for low demand • Faster production/ availability of single units	• Customers: cheap, fast convenient products; increased risk for fake, low quality products • Designers: risk of knowledge leak • Manufacturers (existing): Reduced order volume • Suppliers: fewer fixed relationships with customers • OEM's: partnerships with AM supply platforms required • Society: new companies

Table 3.3 continues on next page.

Table 3.3: CIMO per mechanism and disruptive effects on SC stakeholders *(continued)*

	Context	SC Intervention	Mechanism	Desired SC Outcomes	Disruptive Effect on Stakeholders
IV	• Long-tail spare parts	• AM machine • Supply of raw materials • System for digital designs	• Digitized-stock	• Reduced finished goods inventory • Improved parts availability • Reduced transportation	• Suppliers: Reduced warehousing and transportation leading to reduced 3PL's • Society: Reduced need for personnel
V	• High performance applications (aeronautics)	• AM machine • System for digital design • Design for AM knowledge	• Buy-to-fly spin-offs	• Reduction of material cost • Reduction of lifecycle cost • Reduced footprints	• Engineers/educational institutions: design for AM knowledge required • Suppliers: reduced need for raw materials • Society: reduced footprints
VI	• Assemblies manufacturing • Aviation/ Construction industry	• AM machine • System for digital design • Design for AM knowledge	• Functionality-integration	• Reduced production, assembly and raw material cost • Less assets • Reduced production & assembly lead-time	• Engineers/educational institutions: design for AM knowledge required • Suppliers: reduced SC steps reduces need for production/assembly equipment • Society: fewer SC steps reduces need for production and assembly personnel

which in turn reduces fuel consumption and carbon footprint during operation, and reduces the need for raw materials, thus having a positive influence on society as a whole. Design-for-AM knowledge is a key requirement, and educational institutions need to adapt to accommodate this. Kothman and Faber [67] have outlined the SC benefits of AM for the construction industry in terms of integrating functionalities during manufacturing. This reduces SC steps, suppliers and cost, as well as increasing building speed and improving footprints.

We use the CIMO structure in Table 3.3 and extend this by outlining the related game-changing effects for the SC stakeholders.

3.5 Discussion

This section discusses the AM SC mechanisms we developed through systematic literature synthesis of 61 peer reviewed articles in Section 3.4.2 and the game-changers discussed in Section 3.4.3.

When using AM in SC design, traditional SC mechanisms may evolve to a more advanced level and vastly improve SC performance. Related to Research Question 4, Table 3.4 summarizes the traditional and the constructed AM SC mechanisms from Section 3.4.2. We note that mass-customization may become unlimited, production decisions may be postponed to the very last minute before use, stock-keeping may change from physical to digital, different shaped products may be produced in batches allowing economies-of-scale to become a reality for individualized products, buy-to-fly ratios may improve and create spin-offs during use, and integration of functionalities may reduce SC steps in line with disintermediation.

Table 3.4: Traditional SC vs. AM SC mechanisms

Traditional SC mechanisms	→	AM SC mechanisms
Mass-customization	→	Co-customization
Postponement	→	In-situ & on-demand
	→	Digitized stock
Economies-of-scale/batches for identical products	→	Shared-economies
Buy-to-fly	→	Buy-to-fly spin-offs
Disintermediation	→	Functionality-integration

Several relevant points can be made here. First, although we present these mechanisms as single mechanisms, in reality, often a combination of these mechanisms will exist. This is in line with Hsuan Mikkola and Skjøtt-Larsen [33], who have proposed that mass customization and postponement are interrelated. For example, Kothman and Faber

[67] have described in-situ and on-demand 3D-printed construction elements, with integrated cooling functionalities and using a highly-customized, co-created design, thus integrating three AM SC mechanisms.

Second, other SC mechanisms may exist. For example, Baumers et al. [89] have described a mechanism using the 'if you can't measure it, you can't manage it' paradigm. Here, the single-step nature of AM leads to a simplified SC, which leads to a simplified production energy consumption measurement. The minimum cost configuration makes producers adapt their SC design—which reduces energy consumption and thus improves SC carbon footprint outputs. Moreover, Holmström, Liotta and Chaudhuri [88] have identified two potential SC practices ('incremental product improvement' and 'dynamic SC redefinition and reconfiguration') that may be implemented in the future. However, since these practices have not yet been observed, they are not included in our synthesis. In principle, any traditional SC mechanism, e.g., dual sourcing or closed-loop supply chains, may be affected in the future.

Third, the mechanisms presented here appear to consist of multiple 'building blocks', which can be seen as the underlying characteristics of these six AM SC mechanisms, see Figure 3.8. Some of these building blocks originate in the technical (additive) nature of AM, while others are not AM technology specific. A comprehensive understanding of these individual building blocks, and how they combine, is essential to the design of improved supply chains.

Figure 3.8 shows a general conceptual model of an AM SC design using the CIMO structure and extended with the inclusion of potential game-changers. It is worth noting that the future is unknown, and some effects may or may not occur, while other, as yet unforeseen consequences, may also occur [50].

3.6 Conclusions

This article contributes to the AM SC design knowledge base by building new theory and constructing six AM SC mechanisms to improve SC design. Furthermore, we compare these mechanisms to 'traditional' mechanisms used in the design of SCs for manufacturing purposes. This article also contributes to the innovation knowledge base by determining potentially game-changing effects of AM SC design. The method presented in this article can be used as an example for other researchers investigating the impact of new (other than AM) technologies on SC mechanisms and disruptions. While AM for manufacturing purposes is not yet fully mature, general and logistics managers should carefully observe the developments in AM—in particular the elimination of the barriers preventing the roll-out of AM. Once these barriers have been eliminated, this article can also be used by managers to fully exploit the potential AM

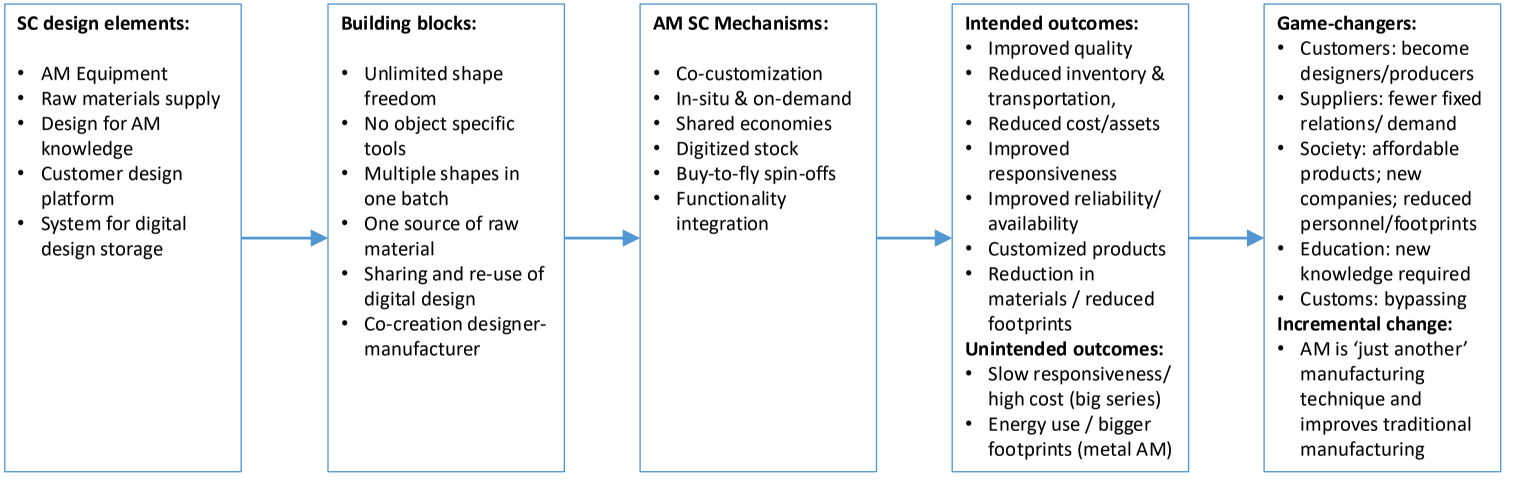


Figure 3.8: Summarized conceptual relationships.

has in terms of designing strongly improved supply chains. Alternatively, businesses can experiment with AM and find segments to 'cross the chasm' [90] between early adapters and early majority [91]. In such cases, a well-designed supply chain will be a key enabler for a successful business model.

Moreover, innovators and policy makers can use the results of this article to understand the possible game-changing effects of AM. Our findings can be summarized as follows.

(RQ 1) In the current state of development, AM is used for many different low-demand applications, e.g., in healthcare, (car) manufacturing and the aeronautics industries, and many technological and regulatory issues need to be taken into account. Supply chains may get shorter and simpler, and the sequence of steps may change. Raw materials may replace final products and digital files may replace physical products. Fewer raw materials may be used from just one source, thus changing relationships with suppliers. IT systems may be used for communication and design by customers, and new design knowledge may be required. AM may reduce SC costs and the need for assets. Responsiveness and other performance outcomes may improve, and on the other hand, unwanted outcomes may also occur.

(RQ 2) We synthesized existing theory and constructed six AM SC mechanisms. We explored their conceptual relationships, connecting SC design and SC outcomes. The resulting AM SC mechanisms are: (1) co-customization; (2) in-situ and on-demand; (3) shared-economies; (4) digitized-stock; (5) buy-to-fly-spin-offs; and (6) functionality-integration.

(RQ 3) We determined the game-changing effects of AM SC-design for the stakeholders. These include: customers turning into designers and manufacturers; reduced demand for suppliers and fewer 'fixed' relationships; affordable products for society; reduced need for personnel and reduced carbon footprints. Moreover, new businesses may appear and new (design-for-AM) knowledge may be required from educational institutions.

(RQ 4) We suggest that traditional SC mechanisms can evolve to an advanced level. Mass customization may become unlimited; production decisions may be postponed to the very last minute before use; stock-keeping may change from physical to digital; economies-of-scale may become a reality for individualized products; buy-to-fly ratios may improve and create spin-offs during use, and integration of functionalities may reduce SC steps in line with disintermediation.

Of course, our study has several limitations that give rise to further research. First, although we followed the research guidelines for SLR, it is possible that some bias may have occurred [42]. In step 4 (Section 3.3.4), due to practical limitations, we did not use a blind selection process in our peer review, nor did we use multiple

researchers as a way of preventing selector bias. In addition, in step 5 (Section 3.3.5), coding and expectancy biases may have occurred when analyzing and synthesizing our results, since, again, we did not involve multiple researchers. Second, we only used peer reviewed articles to ensure that only high quality sources were included. However, AM is an innovative and fast-changing field, while the knowledge created in academic articles lags behind due to the relatively long processing times. The use of grey literature would have had the benefit of being more up-to-date. An additional reason for further research is that technological developments will continue to be made in AM. In addition, other new technologies, e.g., block chain, will provide new building blocks that may also cause changes to existing SC mechanisms, and result in disruptive effects for stakeholders. Consequentially, some may become redundant and new parties will emerge. New (combinations of) mechanisms may be found that lead to new SC solutions. Our literature synthesis enhances the current understanding of the evolution of SC design and the potential disruptions that can arise following the implementation of new technologies. In a final reflection on our literature synthesis, we emphasize that, although the selected articles have been peer reviewed and provide interesting insights, they are mostly based on experiential knowledge rather than empirical results. We recommend that future rigorous empirical research includes case study research using the DSR strategy [24]. In terms of both theoretical and practical considerations, there is still a lot of work to be done.

Appendix 3.1

Table A3.1: Literature

	AM SC Context	Authors
Industry	Aeronautics	[14,62,66,75,80,84,92,93]
	AM Service Providers	[8,87]
	Construction	[66,67,69]
	Utilities (energy, mining, oil)	[62,66]
	Food	[94]
	Healthcare	[8,18–20,62–64,68,88]
	Humanitarian aid	[21]
	Manufacturing	[66,78,79,82,86,95–104]
	Retail	[60]
Products	Components & assemblies	[62,66,67,78,82,84,86,92,98, 100,101,104]
	Consumer products	[8,60,94,95,97,102,105]
	Houses	[67]
	Medical devices	[8,18–20,62–64,68]
	Spare parts	[13,14,16,21,22,62,66, 79–81,93]
	Tools	[8,66,99,101]
Sales channel	Business-to-business	[6,13,14,18–22,60–64,66, 68,72,75–78,80–84,86,89, 93,96–101]
	Business-to-consumer	[67,73,76,94,95,102,105,106]
	Customer-to-customer	[60,61]
Product life-cycle phase	Development (prototyping)	[8,16,17,19,60,61,63,72,73, 75,76,88,92,97,98,100,104]
	Both development and production	[6,20,62,67,68,72,78,81,87, 94,101,102]
	Production	[6,8,13,16,18,19,60–62,64,66, 67,72–79,81,82,84,86–88, 95–97,99,101,107,108]
	Operation/use	[8,19,66,83,84]
	End-of-life (repair)	[14,21,22,62,66,80,93]
Demand	Low (or very low) demand/single units	[13,14,16,22,61,62,66,67,72, 73,76,81,82,86,88,92,93,95,9 6,99,109]
	High demand fluctuations	[93,95]
	Immediate availability (not) required	[13,18]
	Systems difficult to access	[14,21,22,62]
	Product unavailability, shortage	[14,81]
Barriers	Product, (surface) quality, accuracy, durability, strength	[15,57,60,66–68,72,75,78,95, 103,105,106]
	Material availability	[57,68,84]
	Material characteristics	[67,73,75,105]

Table A3.1 continues on next page.

Table A3.1: Literature *(continued)*

	AM SC Context	Authors
	Material cost	[17,57,72,103]
	Lack of process automation	[66,67]
	Low production speed	[75,78,84,103]
	Reliability, stability of print process	[57,67]
	High machine cost, limited build sizes	[57,69]
	Limited process parameter control	[109]
	AM and AM design knowledge required	[20,57,61,73]
	Awareness and acceptance of employees, management and customers	[57,104]
	Lack of government support; cost calculation knowledge, vendor trust; management support; designers attitude; workers resistance	[103]
	IP unclear	[6,13,60,61,72,73,75,81,87, 103,106]
	Missing legislation and regulations	[15,57,61,64,68,87]
	Liability and warranty unclear	[6,61,66]
	QA, testing and inspection missing	[13,61,66,67,73,75]
Plan	Range of SKU's replaced by one process	[14,22,62,72,76–78]
	Regular SC re-alignment required with increasing AM maturity	[110]
	Design-build-deliver paradigm shift	[73]
	Improved economies of scope in mass-production	[82]
	SC shorter and simpler	[6,22,67,68,76,79,81,84,107]
Source	Network of partners and cooperation with SC partners required	[20,21,73,75,87,111]
	Licencing agreements with OEMs	[87]
	Local supply of raw materials	[66,73,77,101,102]
	Shift from component supply to raw material supply; Reduced dependency on component suppliers; Reduced supply of raw materials	[66,67,72,83,101]
	Outsourcing of AM to service providers/capacity pooling	[13,72,75,81]
	Powerful raw material suppliers	[109]
	Reduced partners in the supply chain	[67]
Make	Engineer-To-Order/Make-To-Order	[6,13,14,16,18–22,60–62,64, 66,68,72,76,79,81,87,94,95, 101,102,107,108]
	Make-To-Stock	[13,18,80,93]
	Central AM configuration	[13,18,60,79,80,93,94,101, 106,109]
	Distributed AM configuration	[6,8,13,14,21,22,57,60–62,66, 68,73–77,80,87,88,102,105, 112,113]
	Distributed manufacturing, central coordination	[60]
	Distributed manufacturing, central design	[20]

Table A3.1 continues on next page.

Table A3.1: Literature *(continued)*

	AM SC Context	Authors
	Distributed scanning, central manufacturing	[87]
	Mobile AM	[69]
	Personal manufacturing (at site of consumer)	[8,69]
	AM production next to TM production line	[101]
	Reduced production steps and machines, assembly, facilities	[61,62,66,76,78,80,81]
	Versatile machine with standardized interface	[62]
Deliver	Reduced need for—and adaptions to—material handling equipment and distribution centers	[61,64,73,75,77,81,84,88,105]
	Reduced stock-keeping and shift to raw material stock-keeping	[6,13,17,60,64,66,68,72,76,79, 81–83,88,93,96,102]
	Reduced transportation	[17,60,64,68,75,76,79,81,83, 87,88,102]
	Change to digital file distribution	[13,21,66]
	Distribution of raw materials only	[66,67]
	Local distribution	[61]
	Production in-transit (mobile AM)	[69]
	At home printing as means of product distribution	[8]
	Transportation modalities require adaptions (e.g., bulk to fine)	[73,77,105]
Return	Enables extension of assets' lifecycle	[66]
	Enables internal recycling	[66]
	Enables use of recycled materials	[76]
	Reduced disassembly efforts	[78]
	Reduced waste material	[64]
	Reduced polution, landfill	[20,67,72,78]
Enable	Digital catalogue/database required for sharing and retaining of digital images	[13,19,66,73,74,87,101]
	Secure infrastructure required	[87]
	Combination with other electronic services	[14,107,108]
	Digital file co-creation by engineer and customer, design and customer integration through online platform	[60,61,66,73,88,101,102,113]
	Shift from conventional inventory management, using Bill Of Material, to individual tracking	[6,61]
	Online platform required	[60,84]
	Distinction between roles disappears; redistribution of tasks in the SC	[8,67,73,76]
	Reduced manual intervention; Reduced knowledge and skills required; Reduced need for personnel and overheads	[18,61,62,76,80]
	Production done by customer	[8,60,102,105]
Cost	Reduced inventory cost (includes finished goods, raw materials, work-in-process, safety stock, obsolescence)	[6,13,17,18,60,61,64,66,67, 72,73,75,76,79,81,82,86,88, 93,95,96,101,102,109]

Table A3.1 continues on next page.

Table A3.1: Literature *(continued)*

	AM SC Context	Authors
	Increased production cost (per piece); inefficient capacity utilization	[8,13,19,74,79,98]
	Reduced production cost (assembly, energy, set-up, efficiency)	[6,62,78,84,86,92,97,99,101]
	Products customized at no additional cost	[8,62,88]
	Increased transportation cost	[13,80]
	Decreased transportation cost	[17,60,64,66,67,75,76,79, 83,87,102]
	Reduced final product cost (low volumes or complex products)	[15,88,105]
	Reduced lifecycle cost (includes operating, logistics, opportunity, warehouse, SC, material handling, warehouse cost)	[19,21,22,61,64,66,75,79–81, 84,87,88,95,102]
Assets	Extended lifecycle	[66,88]
	Reduced parts for specific equipment (machines, facilities, tools)	[6,8,60–62,66,69,72,74–76, 80,86,96–98,101,105]
Responsiveness	Increased time for production, assembly or repair	[80,95]
	Decreased production time (small series), assembly time; Decreased product development, (re) design, time to market	[6,8,13–16,18–22,57,60,62, 66–69,72,73,75,76,78,80, 82,86,88,92,96–101,113]
Reliability	Improved availability of products/services	[14,21]
	Improved product quality, reliability	[16,19,63,64,66,67,86,101]
	Improved consent and trust	[19]
	Improved replicability	[20]
	Improved reliability of delivery dates	[6]
Flexibility	Improved management of demand swings; Manufacturing volume and product flexibility; High customization, individual design	[8,14,15,22,62,67,69,72,76,79, 80,95,96,101,113]
Security	Increased risk e.g., for knowledge leak	[66,87,102]
	Reduced dependency on component suppliers	[6,13]
	Improved product safety; Reduced risk for infection	[19,64]
	Reduced risk for law suits	[96]
Sustainability	Reduced (carbon) footprint, energy, emissions, pollution, waste, materials	[20,64,66,67,75,79,84,101]
	Extended lifecycle of assets	[66]
	Social: labor shift when manufacturing near consumption	[88]
Innovation	Improved design, highly complex, highly customized, integrated functions	[15,20,61,62,67,75,81,88]
	Enables co-creation	[17,19,57,60,66,73,76,94, 101,102]
	Encourages innovation; Incremental product improvement/introduce new technologies to products in use	[22,88]

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PART 2
PRACTICE

"It is always wise to look ahead,
but difficult to look further
than you can see"

Winston Churchill

CHAPTER 4



A case study on central or distributed additive-manufacturing of surgical guides

This article is a co-creation with Aalto University and is authored by Victor Verboeket, Siavash Khajavi, Harold Krikke, Mika Salmi and Jan Holmström. This article was submitted to and rejected by (with the option to resubmit) the international (peer-reviewed) journal 'Computers in Industry'.

Abstract

This article compares the speed and cost performance of centralized versus distributed configurations in relation to a supply chain (SC) in which an Additive Manufacturing (AM) service provider supplies medical care products to University Medical Centers (UMCs). Currently, UMCs outsource patient-specific product manufacturing to a centralized AM service provider, but are considering the use of distributed (on-site) AM to speed-up the supply chain if the cost is acceptable. The drivers behind this are a desire to improve the treatment learning loop and patient well-being.

We gathered real-world data, and evaluated future scenarios. Our results show that, using currently available technology, distributed AM reduces delivery time from 54 to 27 hours but triples the cost. Lead time must be further reduced, as cooling is still a time-consuming process, while high costs are caused by measures taken to prevent dust-dispersion related to the powder bed fusion AM process. Future AM machines may allow for faster cooling and solve the dust-dispersion issue.

This article contributes to our understanding of the relevant factors in deciding whether central or distributed supply chain configurations are used in the AM production of patient-specific medical care products. Furthermore, it provides guidance for decision-makers at University Medical Centers, AM service providers, and equipment manufacturers.

4.1 Introduction

Over the last few decades, technological developments have significantly changed the world we live in. Digitization has moved into every business and household and is increasingly integrated into the physical world. As a result of these advancements, it has been necessary for supply chains to adapt to these evolving – and sometimes conflicting – requirements. Mentzer et al. (2001) define a supply chain (SC) as "a set of three or more organizations or individuals, directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to the customer". The goals of SC management are to produce at low cost, to deliver high customer value, and to provide a competitive advantage. To improve competitiveness, companies are always on the lookout for new solutions, often enabled by new technologies such Additive Manufacturing (AM).

AM is a technique whereby material is added layer by layer – in contrast to traditional (subtractive) manufacturing, in which material is gradually removed from an initial block to achieve the intended shape (ISO/ASTM, 2015). AM allows for the production of complex geometries and mass customization without additional costs. Fawcett and Waller (2014) provide examples of potentially disruptive effects on SCs – when, for instance, manufacturing in low wage countries moves from factories to households. Steenhuis and Pretorius (2017) describe how AM can disrupt in one context while causing only minor changes in another, while Holmström et al. (2010) and Pérès and Noyes (2006) argue that AM is only useful for particular applications. AM can be used in many different medical applications such as preoperative models, implants, tools, and instruments (Tuomi et al., 2014). Some of these applications are still in the research phase but others are already commercially available.

Academic literature on the effects of AM on SC designs is scarce (Holmström et al., 2016, Waller and Fawcett, 2014). In addition, Verboeket and Krikke (2019b) suggest that the central versus distributed positioning of AM in the SC – and the related cost and responsiveness tradeoffs – should be a key research topic in SC design. To date, Khajavi et al. (2014) have investigated central versus distributed configuration decisions in relation to a spare parts SC, and Emelogu et al. (2016) have investigated the economic feasibility of changing from traditional manufacturing to in-situ AM of biomedical implants. Among the research articles written about the use of AM for medical applications, only a few have utilized real-world case material e.g. Emelogu et al. (2016) and Oettmeier and Hofmann (2016). However, these articles are generally exploratory in nature or they compare AM with traditional manufacturing and fail to compare SC configuration decisions within an existing AM SC design. The aim of the current article is to reduce the knowledge gap on central versus distributed SCs by studying a real-life SC in which an AM service-provider supplies patient-specific medical care products to University Medical Centers (UMCs). Our contribution is to provide

insights into the key decision-making factors related to switching from a centralized to a distributed SC design configuration, considering the trade-offs in SC cost and responsiveness (speed) performance. This research will help to inform decision-making and provide opportunities for interventions at medical centers, AM service providers and AM equipment manufacturers.

The main goal of the UMCs is to improve treatment quality and patient well-being, in addition to enhancing their knowledge about treatment options. In line with Holmström et al. (2017), who mention that the use of direct digital prototyping may accelerate and simplify in-house design, UMCs seek to improve the treatment learning loop. By increasing the speed of the feedback – as a result of changing from centralized to distributed (in-house) AM of patient-specific medical care products – 'experiential learning' (Kolb and Kolb, 2009) can improve.

The remainder of this article is organized as follows: In Section 4.2, we review the existing literature. A description of the research methodology is provided in Section 4.3. This is followed by the results (Section 4.4), the discussion (Section 4.5) and the conclusions (Section 4.6).

4.2 Literature review

This section introduces relevant SC concepts and examines concepts related to additive manufacturing. Moreover, it explains the effects of AM on SC design and outlines the design propositions.

Supply Chain Management (SCM) is a relatively new management field originating in logistics. Whereas logistics mainly focuses on the flow of materials, SCM takes a more holistic approach and includes the flow of information and money. With the emergence of the SCOR model (APICS, 2018), SCM definitions have been standardized and thus the benchmarking of processes and performances have been simplified. The performance of a SC is measured by SC outcomes, and our research focuses on the traditional SC outcomes 'cost' and 'responsiveness' according to the SCOR definitions. Costs are defined as the 'total SC management costs', i.e. the sum of the costs associated with planning, sourcing, making, delivering and returning orders. Responsiveness is defined as the 'order fulfillment cycle time', the time from order receipt to order acceptance (APICS, 2018).

Having a well-designed SC is strategically vital for a firm's competitiveness (Fawcett and Waller, 2014). A SC design comprises of choices related to manufacturing, inventory, assortment, personnel, ICT and transportation modalities (Chopra and Meindl, 2013). In the current research, we explore one of the most important decisions in SC design – when to switch from centralized to distributed SC configurations.

SC designs are heavily influenced by technological and societal changes. The World Economic Forum states that society is at the verge of the fourth industrial revolution (Swab, 2017) where increasingly fast computing, for instance mobile supercomputers and Artificial Intelligence (AI), is revolutionizing civilizations. Computer technology is increasingly penetrating and digitizing supply chains. Büyüközkan and Göçer (2018) define a digital supply chain as 'a smart and value driven process that generates business value with analytical processes and technology'. In addition to AM, digital supply chains can include any other digital technology, for instance blockchain technology, internet of things (IoT), Automated Guided Vehicles (AGVs), or combinations of technologies, for instance a 'digital twin' of blockchain and AM (Mandolla et al., 2019).

AM is a collection of techniques which can, depending on the material and the specific technology chosen, be categorized in different ways (ISO/ASTM, 2015). Our research concentrates on 'Selective Laser Sintering' (SLS), which is a powder bed fusion AM technique. AM is also known as rapid prototyping (RP), rapid tooling (RT), rapid manufacturing (RM), or three-dimensional (3D) printing. After the invention of AM, prototyping (RP) applications were the first to appear in the 1980s. As more materials became printable, tooling (RT) applications followed in the late 1980s. Rayna and Striukova (2016) now consider RP and RT applications to be full-grown, in contrast to the manufacturing (RM) applications of final products. Nevertheless, many applications already exist, for instance for industrial (spare) parts (Chekurov and Salmi, 2017, Wagner and Walton, 2016), patient-specific medical applications (Emelogu et al., 2016, Giannatsis and Dedoussis, 2009), houses (Ford and Despeisse, 2016, Kothman and Faber, 2016), consumer products (Bogers et al., 2016, Chiu and Lin, 2016) and for art, hobby, jewelry and fashion (Maresch and Gartner, 2018).

AM has several benefits over subtractive manufacturing, although there are also potential downsides to this process. Benefits include the potential integration of functions into the design (e.g. cooling ducts), or production of multiple components in an assembly. Potential benefits also include the reduction in the amount of raw material required and the fact that no expensive tools (i.e. molds) are needed, thus allowing for the production of (very) small series. The downsides of AM potentially include low production speed, expensive machines and materials, low automation levels and poor (surface) quality. Moreover, regulations and intellectual property rights are often unclear (Durach et al., 2017, Dwivedi et al., 2017, Ituarte et al., 2016, Thiesse et al., 2015).

AM's ability to produce any desired shape makes AM suitable for personalized medical products (He et al., 2006, Huang et al., 2013, Weller et al., 2015). For example, it has been shown that the availability of a digital file can improve the replicability of personalized hearing aids (Oettmeier and Hofmann, 2016), preoperative models can be used as a communication tool to improve trust and consent (Giannatsis and Dedoussis, 2009, Salmi, 2016), implants can speed up surgery (Salmi et al., 2012), and in-operating-room-

on-demand AM of coronary stents can significantly reduce the SC lead-time (Moore et al., 2016). The manufacturing time and cost per part can vary greatly, depending on the AM process used, the build orientation, and the amount of parts made in the production batch (Salmi et al., 2016). According to Walter et al. (2004), the production cost of AM produced parts primarily depends on the product volume – which makes AM particularly suitable for small parts. When using the SLS technique, increasing the ratio between powder and parts (packing density) is crucial to improving the manufacturing time and cost per part (Ruffo et al., 2006). This results in the need to make as many parts as possible in each production run (Khajavi et al., 2018).

The unique characteristics of AM change SC requirements while potentially improving SC performance (Verboeket and Krikke, 2019a). Compared to traditional (subtractive) manufacturing, AM may make SCs shorter and simpler, thus reducing the amount of SC steps (Gebler et al., 2014, Holmström and Partanen, 2014, Holmström et al., 2016), and digital file distribution may largely replace the distribution of goods (De la Torre et al., 2016, Ford and Despeisse, 2016, Holmström et al., 2010). Moreover, the traditional design-build-deliver arrangement may shift (Petrick and Simpson, 2013).

SC configuration decisions relate to the positioning of AM in the SC (Verboeket and Krikke, 2019b). Centralized configurations do exist (Eyers and Potter, 2015, Mellor et al., 2014, Rylands et al., 2016), as well as distributed AM configurations (De la Torre et al., 2016, Durach et al., 2017, Holmström et al., 2017). Moreover, Oettmeier and Hofmann (2016) describe the use of a centralized design combined with distributed manufacturing, in contrast to Rogers et al. (2016), who combine distributed scanning with centralized manufacturing. Eyers and Potter (2015) combine centralized coordination with distributed manufacturing whereas Durão et al. (2017) describe the use of centralized control with different levels of distributed automation. In line with Khajavi et al. (2014), and Emelogu et al. (2016), our research includes centralized versus distributed SC configurations scenarios. Distributed AM may improve responsiveness (speed), e.g. faster repair time, faster time-to-market and faster product availability (Ford and Despeisse, 2016, Khajavi et al., 2014, Mohr and Khan, 2015, Pérès and Noyes, 2006). For patient-specific medical care SCs, a significant reduction of the SC lead time is possible (Moore et al., 2016). Moreover, Oettmeier and Hofmann (2016) have noted that distributed AM results in faster product availability of patient-specific medical care products. This leads to our first proposition:

1. For patient-specific medical care products, moving from centralized to distributed AM SC designs improves responsiveness by providing faster product availability.

Distributed AM may reduce inventory (finished goods) and transportation costs (Bogers et al., 2016, Meisel et al., 2016, Rogers et al., 2016). However, compared to centralized solutions offered by AM service providers, distributed locations have no economies of

scope in terms of equipment utilization, raw material purchasing, labor, and knowledge (Holmström et al., 2010, Wagner and Walton, 2016). Moreover, our research takes technological developments into account, i.e. the prediction that AM machines will become cheaper and faster (Coenen, 2018, Wohlers, 2018) in these scenarios, and a higher level of automation will reduce labor costs (Durão et al., 2017, Khajavi et al., 2014). This leads to the following propositions:

2a. Currently, distributed patient-specific medical care SC configurations reduce inventory and transportation costs. However, due to the absence of economies-of-scope, total SC costs are higher than those associated with a centralized design.

2b. As technology advances, lower machines prices and an increased level of automation will decrease labor costs and make a distributed patient-specific medical care SC configuration cheaper as compared to a centralized SC design.

4.3 Methodology

Kaipia et al. (2017) advocate using case study research for collecting data to be used as input for designing artifacts in a design science research project. Our article also uses case study research for data collection and design science for designing and evaluating future scenarios. Our methodological design is summarized in Figure 4.1.

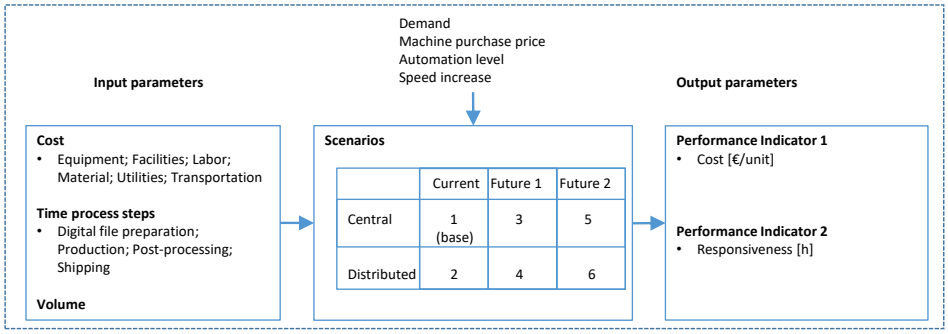


Figure 4.1: Methodological design.

4.3.1 Case study

Yin (2014 p. 16) defines case study research as: 'an empirical inquiry that investigates a contemporary phenomenon (the case) in depth and within its real-world context'. In line with this, case study research was used for data collection – alongside the guidelines provided by Yin (2014) – to ensure research rigor.

We selected this case in line with our aim to contribute to the body of knowledge regarding SC design for medical applications. As stated in the Introduction, the current body of knowledge is quite scarce in this specific field. According to Yin (2014), cases should be analytically generalizable, and this case represents a wider class of AM applications within a medical context.

This study concerns the downstream SC of patient-specific surgical guides (Figure 4.2), which are used for cutting or drilling tools. These personalized tools allow surgeons to plan the exact positioning for cutting and drilling the patient's bones prior to the actual surgery. Being able to personalize these guides means that improvements can be made in terms of surgery quality and first time fit. Besides improving patients' wellbeing, this may save one hour of Operating Room (OR) time. AM is very suitable for the manufacturing of these complex shapes and has been used for this application for several years now. A set used during surgery can consist of multiple pieces. Currently the SC comprises of eight UMCs (located in the Netherlands) where these surgeries are performed. The UMCs are supplied by one (central, outsourced) AM service provider, also located in the Netherlands. The AM service provider uses EOS Formiga P100 AM machines. These machines use the Polyamide SLS powder bed fusion process (EOS, 2018). The UMC innovation lab is the legal manufacturer and uses CT-scan Digital Imaging and Communications in Medicine (DICOM) data to design the surgical guides and then forward the file for manufacturing to the AM Service Provider. After manufacturing, the UMC's innovation lab receives the part, checks the quality, sterilizes the part, and hands it over to the physician for surgery.

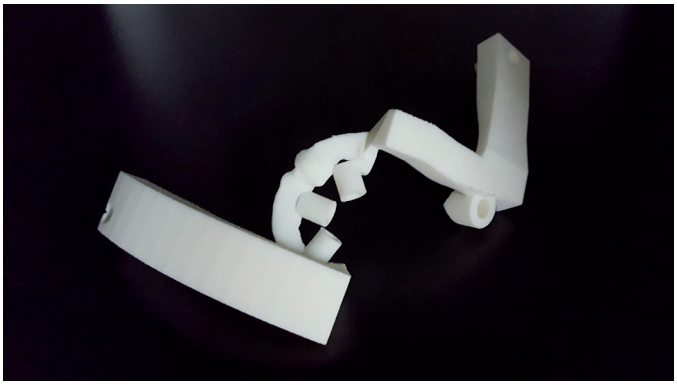


Figure 4.2: Example of a surgical guide.

Our case study research started with the selection of input parameters to calculate cost and responsiveness. The data was collected from one of the UMCs. This UMC is exploring the idea of in-house AM production – at an acceptable cost – for rapid feedback, in order

to further increase their knowledge. This would require AM production to take place on-site at each UMC and could facilitate a process whereby 3D design knowledge is shared between all eight UMCs. Shared knowledge enables reuse of designs and allows for economies-of-scale of the design. In this way, the role of the AM service provider changes from being a provider of finished products to being a provider of materials, the (latest) technological knowledge, and (ownership of) machines.

The desire to have distributed in-house AM is explained by a quote from an interview with a UMC engineer:

> *"The prototyping and production process are more or less integrated: prototypes are continuously created and immediately used. If an improved method is discovered, this learning is immediately applied in all future products. The learning curve advantage of in-house AM production can be explained by an analogy with owning a household saw compared to borrowing a saw from your neighbor: Although –theoretically – in both cases, the saw is readily available, a certain threshold exists when having to obtain the saw from your neighbor. The saw is not as easily accessible, which limits 'playing around' with it and the related creativity and the experiential learning curve."*

4.3.1.1 Data collection

The data collection process followed the Yin (2014 p. 155) approach, using logical models and time study maps for analyzing case study evidence. To make sure data was collected on all relevant processes, an interview question protocol was developed (Yin, 2014 p. 90). For each SC step, volume, time and cost data were gathered, which allowed for calculations to be made of the cost and responsiveness outcome measures.

The AM service provider's CEO was the primary source of information concerning the service providers' processes. Observational data, ERP data and employee interview data were also collected. Moreover, video conference interviews were conducted with an engineer of the UMC innovation lab. The transcripts of the taped interviews were verified by the interviewees. This information was then used for drafting the current processes (base case), see Figure A4.1 (Appendix 4.1). The collected data and process map were validated by the interviewees and were used to develop and calculate the future scenarios outlined in the next section.

4.3.2 Scenario design

Scenario analysis (Varum and Melo, 2010) can help to identify and evaluate realistic future options (Cornelius et al., 2005). Khajavi et al. (2014) have used scenario analysis to investigate SC optimization by comparing centralized versus distributed configurations in an industrial spare parts context. We used a three-step approach for strategic SC planning suggested by Sodhi (2003): the scenarios were built, planned (i.e. the

calculations were made) and validated by the researcher and by the field representatives before being presented as the results (Figure 4.3).

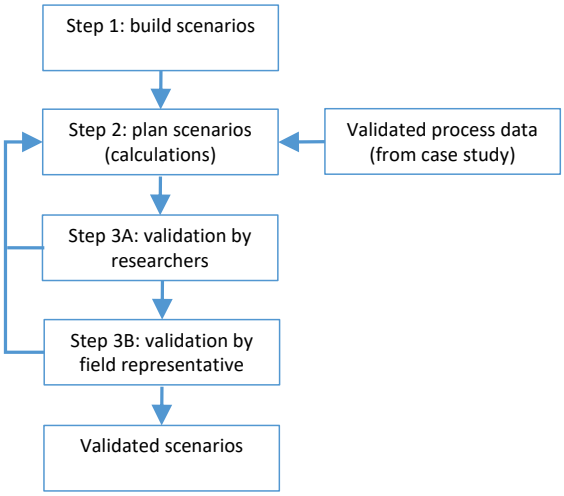


Figure 4.3: Scenario planning process.

4.3.2.1 Building the Scenarios

The candidate scenarios were identified and the key influencing factors were determined (Sodhi, 2003). In line with Khajavi et al. (2014) and Emelogu et al. (2016), we varied the SC configurations between centralized and distributed AM production. Comparisons were also made between current and future states of technology. Scenarios reflecting the current state of technology refer to the EOS Formiga P100 with a purchase price of 250k€ (EOS, 2018). To examine the obstacles associated with each SC design, we included AM machines with different costs, sizes, and capabilities. These alternative machines are called future 1 and future 2 machines. The specification of the future 1 machine is based on the upcoming Formlabs Fuse One AM machine with a 20k€ purchase price. This machine has comparable specifications to the EOS Formiga P100 and is verified for medical devices (processing and materials). However, it has a smaller production chamber and a weaker laser (Formlabs, 2018). The specification of the future 2 machine is assumed to be similar to that of the future 1 machine, apart from the fact that it also has a dual chamber for printing and internal cleaning tools. Similar technologies are already in use in professional desktop SLS machines such as Sharebot's SnowWhite (equipped with two tanks, one for powder and one for part removal). We assumed that such a machine does not require facility preparation activities such as air conditioning or foundation construction and eliminates the need for cooling parts outside of the machine. The six scenarios are displayed in Table 4.1 and Figure 4.4.

Table 4.1: SC Scenarios

		SC configuration	
		Centralized AM at AM service provider	**Distributed** AM at all eight UMCs
State of technology	**Current AM** Existing EOS P100 machines at 250k€	Scenario 1 (base case)	Scenario 2
	Future 1 AM Upcoming Formlabs Fuse one at 20k€	Scenario 3	Scenario 4
	Future 2 AM Fictional AM machine which eliminates out-of-machine cooling and has a dual chamber for printing and cleaning at 20k€	Scenario 5	Scenario 6

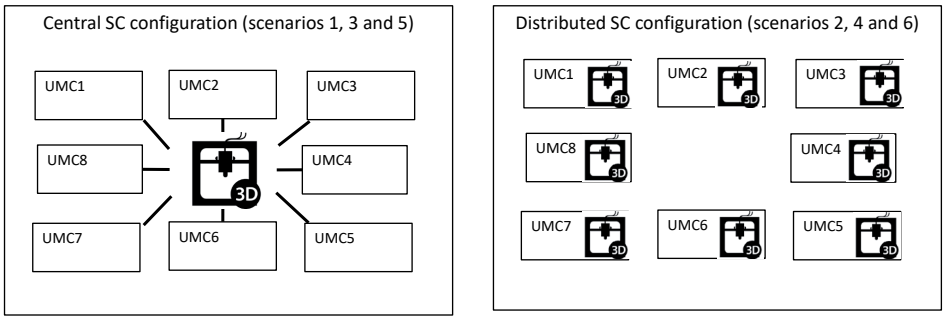


Figure 4.4: Centralized and distributed SC configurations.

The various scenarios and the sensitivity analyses were designed to test the design propositions; the relationships are explained in Table 4.2.

Table 4.2: Propositions and scenarios

Proposition	Scenarios and sensitivity analyses
1.	• Responsiveness performance Scenarios (1, 2 and 3) vs (2, 4 and 6); • Sensitivity analysis on production speed.
2a.	• Cost performance Scenarios (1, 2 and 3) vs (2, 4 and 6); • Sensitivity analysis on demand; • Sensitivity analysis on machine price.
2b.	• Cost performance Scenarios (1) vs (4); (1) vs (6); (3) vs (4); (5) vs (6); • Sensitivity analysis on automation level.

4.3.2.2 Scenario calculations

In several iteration-rounds, the scenarios and calculations were refined and discussed with the AM service provider CEO until a final consensus was reached. Note that possible wastes (e.g. waiting times) were ignored, also note that the processes end upon delivery at the UMC and inspection and sterilization time (steps 21 and 24, see figure A4.1, Appendix 4.1) were not included. The following 'total SC management costs' (APICS, 2018) elements were included in the calculations:

1. Equipment: AM machine investments and maintenance, and the investments in post-processing equipment (blaster, brush);
2. Facilities: Facility adaptations (foundation preparation, air-conditioning, and air cleaning). Space acquisition or rental costs were excluded;
3. Labor: Operator training and operational costs as well as supervisor costs (one supervisor per six operators);
4. Material: Polyamide raw material;
5. Utilities: Energy for pre-heating and manufacturing;
6. Transportation: Finished products from AM service provider to UMC, outsourced.

To enable a comparison of the scenarios, we calculated the cost per part in Euros (€) and used the total SC cost over a five-year period divided over the cumulated 5-year volume.

$$Cost\ per\ part\ in\ each\ scenario = \frac{\sum_{year\ 1}^{year\ 5} cost(Equipment, Facilities, Labor, Material, Utilities, Transportation)}{\sum_{year\ 5}^{year\ 1} Demand\ volume}$$

This calculation period is in line with the AM machine depreciation period of EOS P100 machines. For calculating scenario costs, a SC model for each scenario was modeled in Microsoft Excel. Verification of formulas and results was achieved through four iterations of the initial model in conjunction with the expert opinion of the AM service provider's CEO.

The 'order fulfillment cycle time' (APICS, 2018) was calculated using the SC map. The following steps were included in the calculation:

1. Digital file preparation: file check, nesting;
2. Pre-production: preparation, preheating;
3. Production: 3D printing process;
4. Cooling: cooling inside and outside of the AM machine;
5. Post-production: cleaning, quality check, storage, packing;
6. Transportation: (outsourced) shipping of finished goods.

The sum of the steps was calculated for the average demand in the 5-year period in hours (h), using the following formula:

$$Average\ responsiveness\ of\ each\ scenario = \frac{\sum_{year\ 1}^{year\ 5} time(Dig.file\ prep, Pre-prod, Production, Cooling, Post-prod,\ Transportation)}{\sum_{year\ 5}^{year1} number\ of\ machine\ runs}$$

4.4 Results

In this section, we present the scenario and sensitivity analysis.

4.4.1 Scenario analysis

A set of surgical guides consists of several parts; in the calculations, we assumed that a set, on average, consists of two parts. The base case scenario starts with a volume of 240 sets, equaling 480 units/year. Assuming this doubles yearly, this leads to a cumulated 5-year demand of 14880 units. The current machine price is 250k€ (EOS, 2018), whereas the future technology scenarios consider a machine purchase price of 20k€ (Formlabs, 2018). The results in terms of cost and responsiveness of the six scenarios are displayed in Figure 4.5.

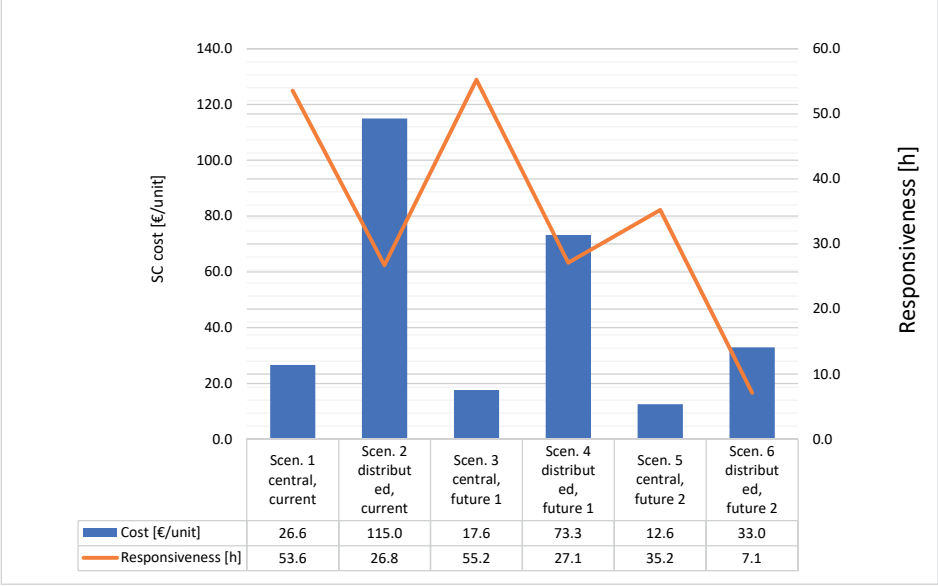


Figure 4.5: Cost and responsiveness related to the different scenarios.

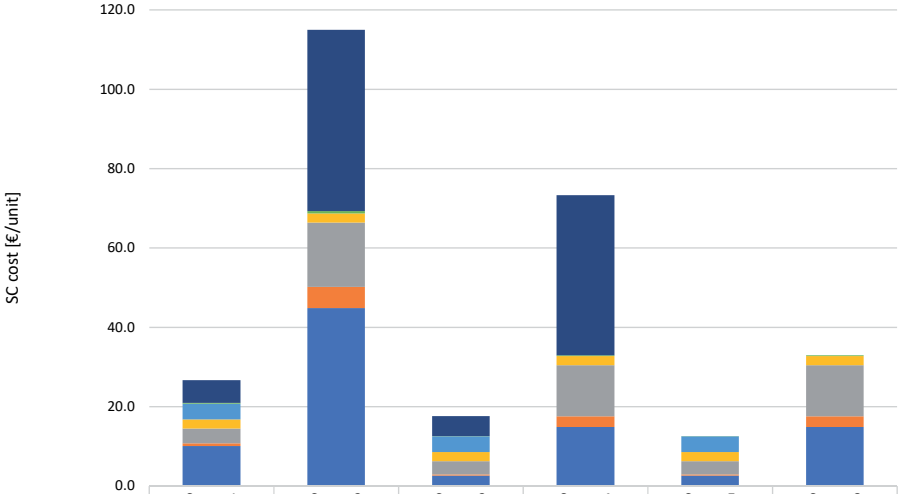
The analyses show that the centralized scenarios perform better on SC costs. However, with regard to responsiveness (order fulfillment cycle), the distributed scenarios perform better than the centralized SC scenarios.

If the UMC – bearing in mind the technological advances that will be made in the near future (Future 1, Formlabs Fuse One) – would have to decide between centralized and distributed SC configurations, Scenarios 1 and 4 should be compared. This comparison shows that the unit cost of the distributed SC configuration is almost three times higher than that of the centralized SC configuration. Additionally, the responsiveness almost halves.

When incorporating Scenarios 5 and 6 (where we assume that the 'future 2' fictional, cheap, dual chamber, fast cooling solution is commercially available), interestingly, the costs of Scenario 6 are close to those of Scenario 1 (6.4€/unit SC cost difference). This illustrates the importance of cheaper AM machines with internal part cleaning capabilities when considering the cost-effectiveness of distributed SCs. Moreover, Scenario 6 is about 46.5 hours faster than Scenario 1. This scenario provides feedback within one working day and may support the desired fast feedback loop at an acceptable cost.

Figure 4.6 displays the major cost components of each scenario.

The machine costs are higher for Scenarios 1 and 2 (based on current technology), but are significantly lower for the future 1 Scenarios 3 and 4. This is due to the high purchase price of the EOS SLS AM machines at 250k€. The costs that are needed for adjusting the production space are very high in the distributed SC scenarios as compared to the centralized SC scenarios. This is mainly due to the high costs required to make adjustments to the eight facilities in order to prevent the dust dispersion caused by production and post-processing activities (cleaning and tumbling). The magnitude of this issue becomes clear when visiting an AM service provider using this SLS/Polyamide technology – production areas are covered in a thin layer of dust. This is particularly unacceptable in a hospital context, and dust prevention measures are required such as air-tightening the facilities and installing air-cleaning equipment. In consultation with the CEO of the AM service provider, we estimated that these facility adaptations would cost 85k€/facility (including the foundation preparations). However, Scenarios 5 and 6 illustrate that the facility preparation costs can be eliminated once the dust dispersion issue has been dealt with. Now, the biggest obstacles of a distributed SC become AM machine and personnel costs. This is significant, as it shows the importance of technological advancements in enabling distributed AM for medical applications. As the machines become cheaper and offer part-cleaning internally and in one run, eliminating the need for production room preparations (e.g. a desktop SLS AM machine), then distributed manufacturing can become cost competitive with current centralized scenarios.

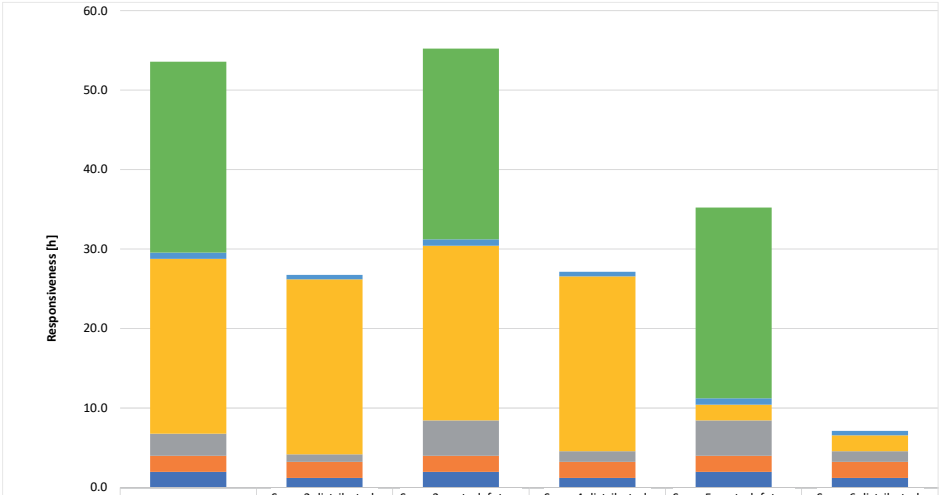


	Scen. 1 central, current	Scen. 2 distributed, current	Scen. 3 central, future 1	Scen. 4 distributed, future 1	Scen. 5 central, future 2	Scen. 6 distributed, future 2
Space	5.7	45.7	5.0	40.3	0.0	0.0
Energy	0.2	0.6	0.1	0.2	0.1	0.2
Transportation	3.9	0.0	3.9	0.0	3.9	0.0
Material	2.3	2.3	2.3	2.3	2.3	2.3
Personnel	3.7	16.2	3.3	12.9	3.3	12.9
Post-processing	0.7	5.4	0.3	2.7	0.3	2.7
Machine	10.1	44.8	2.6	14.9	2.6	14.9

Figure 4.6: Cost breakdown of the scenarios (€/unit).

The transportation costs are high in the centralized scenarios at 3.9 €/unit, while these are non-existent for the distributed SC scenarios. The absolute cost for raw material (including raw material shipping) is identical at 2.3 €/unit for all 6 scenarios. The personnel costs are significantly lower for centralized SC scenarios at 3.7 €/unit, 3.3 €/unit and 3.3 €/unit respectively than for the distributed scenarios at 16.2 €/unit, 12.9 €/unit and12.9 €/unit respectively. The reason behind this vast difference is that in the distributed setting – assuming an equal uniform distribution of the volume over the locations – the total number of machine runs increases. This causes an increase in the overall number of hours of work. Moreover, having the AM machines in eight different locations means there is a need for eight times the initial personnel training. The differences in post-processing costs between the current and future technology scenarios result from cutting equipment costs in half; 5k€ per location which is then multiplied by the number of distributed locations. In all scenarios, the energy costs have no significant impact on cost performance.

Figure 4.7 illustrates the responsiveness breakdown.



	Scen. 1 central, current	Scen. 2 distributed, current	Scen. 3 central, future 1	Scen. 4 distributed, future 1	Scen. 5 central, future 2	Scen. 6 distributed, future 2
Transportation	24.0	0.0	24.0	0.0	24.0	0.0
Post-prod.	0.8	0.6	0.8	0.6	0.8	0.6
Cooling	22.0	22.0	22.0	22.0	2.0	2.0
Prod.	2.8	1.0	4.5	1.3	4.5	1.3
Pre-prod.	2.0	2.0	2.0	2.0	2.0	2.0
Dig. prep.	2.0	1.2	2.0	1.2	2.0	1.2

Figure 4.7: SC responsiveness (hours) breakdown.

The significantly better performance of the distributed scenarios is mainly caused by the elimination of a 24h transportation time. The remaining 27.1h response time of the distributed Scenario 4 can mainly be attributed to the 22h cooling time (2h inside plus 20h outside of the AM machine) required to ensure product quality and accuracy by reducing warping. For Scenario 6, this results in the elimination of that long cooling time outside of the machine. Note that the manufacturing time of the future technology scenarios is longer due to the expected smaller chamber capacity and lower laser power of the AM machines.

4.4.2 Sensitivity analysis

The AM service provider's CEO is in agreement with Wohlers (2018) that demand is rapidly increasing for the AM of patient-specific medical care products – and can double annually. Furthermore, as a result of consulting business literature and visiting AM industry fairs, we can report that AM machine prices are dropping and machines are becoming faster (Coenen, 2018, Wohlers, 2018). Machine manufacturers are also investing in increased automation of secondary processes. With increasing automation levels, manual operator intervention may decrease (Holmström et al., 2016). Accordingly, the sensitivity analysis was performed using the following key parameters:

- Demand volume
- Machine acquisition price
- Automation level
- Additive manufacturing speed

Figure 4.8 illustrates changing (customer order) demand.

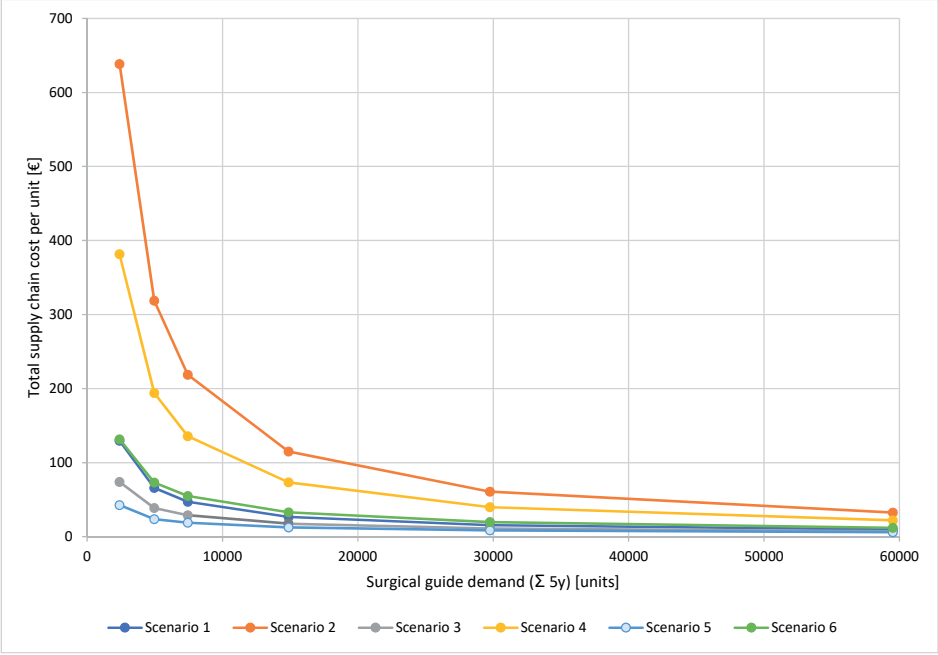


Figure 4.8: Impact of demand volume on SC cost per set (the base case demand is 14880 units).

Set prices drop sharply with increasing demand. When demand quadruples from 14880 units to 59520 units, the unit costs drop by 64% (Scenario 1), 59% (Scenario 3), and 52% (Scenario 5) in the centralized scenarios. Similarly, the unit costs reduce by 72% (Scenario 2), 70% (Scenario 4), and 64% (Scenario 6) in the distributed scenarios. These high unit costs at low volumes are caused by poor machine and production chamber utilization. Moreover, comparing scenarios 5 and 6 illustrates that higher volumes increase the cost-effectiveness of distributed SC as the decrease in the unit price is steeper than that of the centralized SC.

Figure 4.9 illustrates the effects of changing machine acquisition costs. We assumed that machine costs can only vary when new machines are purchased and we therefore only included the future scenarios in this calculation.

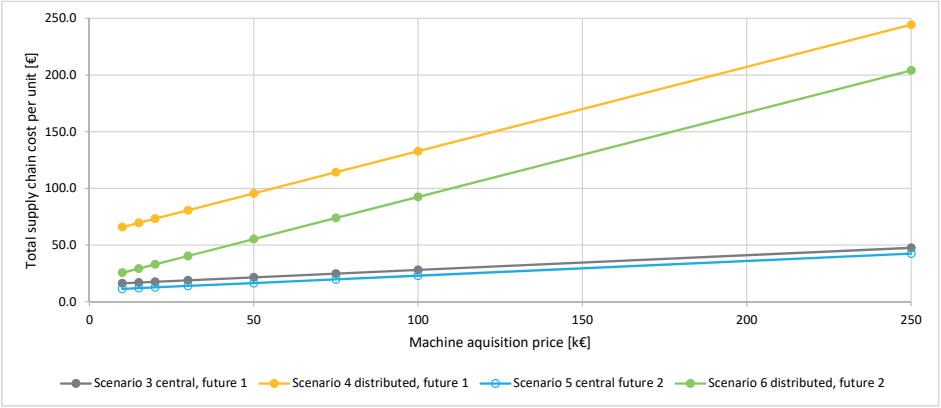


Figure 4.9: Impact of AM machine price on SC cost per piece.

The machine acquisition price sensitivity analysis shows that, if prices drop from 20k€ (Fuse One) to 10k€, the unit costs for centralized Scenarios 3 and 5 are 16.3 €/unit and 11.3 €/unit respectively, which equals a respective reduction of 7% and 10%. For distributed Scenarios 4 and 6, unit costs become 65.8 €/unit and 25.5 €/unit respectively, constituting a 10% and a 23% respective reduction. This shows that the price of an AM machine has a significant impact on the cost-effectiveness of distributed SC configuration implementation for medical applications.

Figure 4.10 shows the results of the sensitivity analysis on the AM machine automation level (0%: no automation to 100%: fully automated).

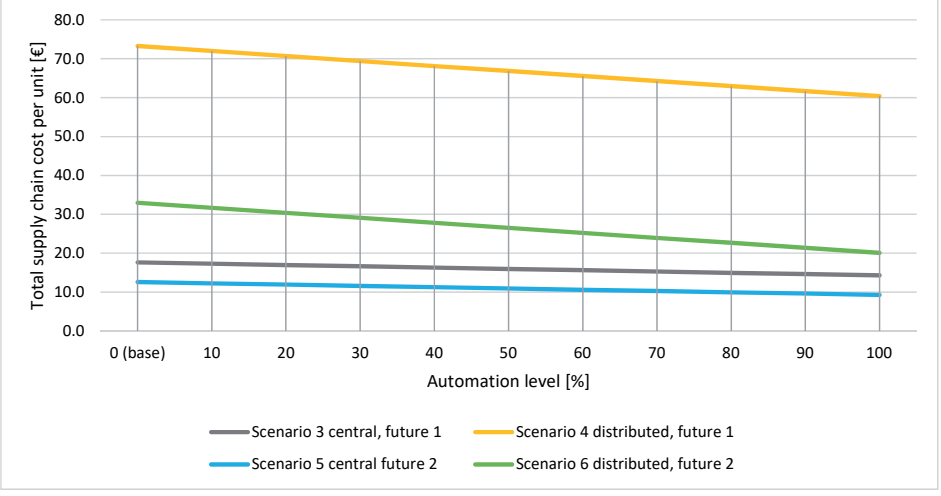


Figure 4.10: Impact of AM pre- and post-production automation level on SC cost per set.

We assumed that no additional investment costs would be required for increasing automation. Only the future scenarios were included in this calculation, since automation level can only improve when existing machines are replaced by newer, more advanced technology.

When the level of automation increases from the current state (0%) to full automation (100% automation), the unit cost drops for the centralized configuration to 14.3 €/unit (19% reduction for Scenario 3) and 9.3 €/unit (26% reduction for Scenario 5). For the distributed scenarios, the unit cost drops to 60.4€ (18% reduction for Scenario 4) and 20.1€ (39% reduction) for Scenario 6. Since the unit cost drop is sharper for the distributed scenarios (4 and 6), we can conclude that increasing the automation level has a positive effect on the effectiveness of the distributed scenario.

Figure 4.11 shows the results of the sensitivity analysis on responsiveness which includes machine preparation, preheating, production and cooling inside and outside of the machine, steps 11 through 15 (Appendix 4.1). Note that the manufacturing process speed for each scenario was calculated for the average production volume per run of a 5-year period.

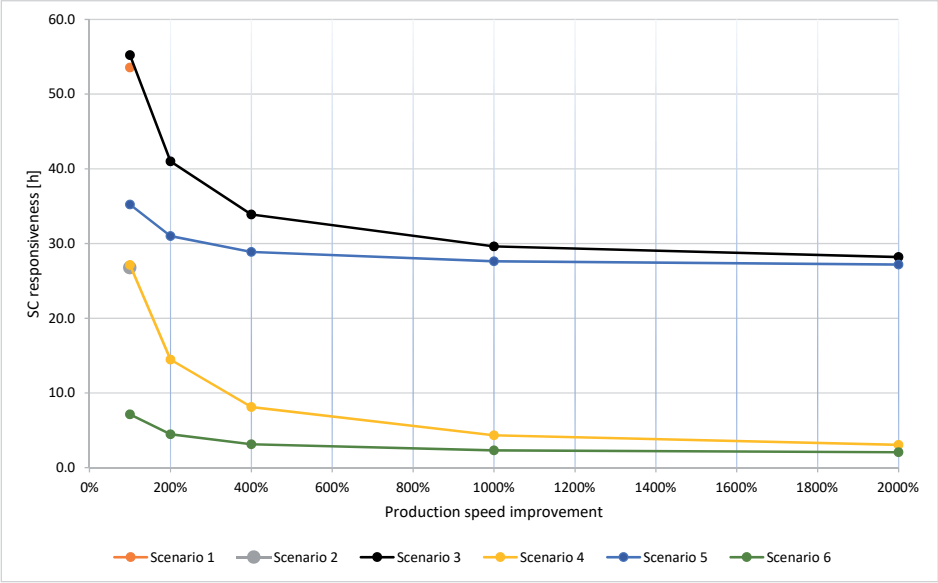


Figure 4.11: Impact of improvement in AM production speed on responsiveness.

Note that the starting point of the technology used for Scenarios 5 and 6 already includes a 20-hour reduction in cooling time outside the machine, as compared to the technology used for Scenarios 3 and 4.

An AM production speed that is four times faster (400%) (including preheating, manufacturing and cooling) improves SC responsiveness of the centralized Scenarios 3 and 5 by 39% and 18% respectively. An AM production speed that is twenty times faster (2000%) improves SC responsiveness by 49%, 23% respectively.

For the distributed scenarios (Scenarios 4 and 6), a production speed that is four times faster can make the products available in 8.1 hours and 3.1 hours, respectively. A production speed that is twenty times faster can make products available in 3.1 hours and 2.1 hours, respectively. Hence a production speed that is four times faster means that products can become available the same working day. This meets the expectations of the UMCs in terms of desired responsiveness and can enable learning cycles and result in improved patient well-being.

Such technological developments in manufacturing speed (including cooling) are not likely to occur using SLS/powder bed fusion with a laser beam, but may be possible to achieve with other AM technologies (e.g.: HP's Jet Fusion technology and similar technologies). As Scenario 6 illustrates, a distributed scenario with fast cooling technology can be very quick even without any acceleration in the other process steps. The reason for this is that shipping and cooling are the most time-consuming steps of the AM process in the centralized SC, as explained in Figure 4.7.

4.5 Discussion

This section evaluates the propositions, discusses the contribution and generalizability of this research, and outlines its limitations.

First, we evaluate the propositions we derived from the literature:

1. For patient-specific medical care products, moving from centralized to distributed AM SC designs improves responsiveness by providing faster product availability.

Comparing the responsiveness performance of the centralized scenarios with the distributed scenarios, we find that the 24h transportation time is eliminated in the distributed scenarios and products can become more quickly available. Nevertheless, Scenarios 2 and 4 still have an approximate 27-hour response time – which is too long in view of the desired learning loop – and is mostly related to the cooling time required for the parts. On the other hand, technological advances, and the use of a machine similar to that presented in Scenario 6, will influence this response time. Once this machine becomes available, the response time of a distributed SC can reduce to 7.2 hours, meeting the requirements of the UMCs. Such improvements are not likely with the current SLS machines, and other AM technology is probably required.

Sensitivity analysis on production speed with shortly-available technology shows that if production speed becomes four times faster, the response time of the distributed scenarios will drop to 8.1 hours, which will also support the learning loop. Such improvements in production speed are more likely to become possible using the SLS technique – for instance, by applying forced cooling.

In relation to the current state of technology, we find only partial support for this proposition since, although the distribution becomes faster, it is not sufficiently fast enough to support the feedback loop; However, with the addition of advancing or new technology, this proposition may become true (since the feedback loop may then be supported).

2a. Currently, distributed patient-specific medical care SC configurations reduce inventory and transportation costs. However, due to the absence of economies-of-scope, total SC costs are higher than those associated with a centralized design.

Since surgical guides are patient-specific, none of the scenarios hold inventory. Therefore, distributed AM will not change the cost of inventory. The cost for transportation reduces to zero in the distributed scenarios. However, since the order volume is divided over eight distributed locations, the utilization rate of the machines is extremely low. To be more specific, when volume quadruples, it is still only 3.4%, 6.5% and 6.5% for Scenarios 2, 4 and 6, respectively. This means that the necessary high investments in machines and facility adjustments, as well as high personnel costs, have to be divided over very low volumes. This results in the absence of economies-of-scope and high per part costs of 73.3€ for Scenario 4 (distributed) as compared to 26.6€ for Scenario 1 (centralized).

Sensitivity analysis shows that quadrupling the demand reduces the unit costs of all scenarios, and distributed SC costs per part come close to the centralized SC costs per part. The gap between the cost per part for the centralized and distributed SCs also widens as the machine acquisition price increases. Therefore, we consider this proposition to be true, and note that sufficient production volume is key.

2b. As technology advances, lower machines prices and an increased level of automation will decrease labor costs and make a distributed patient-specific medical care SC configuration cheaper as compared to a centralized SC design.

Comparing the cost performance of the current technology in centralized Scenario 1 with the soon-available future technology (where machine purchase price drops to 20k€) in distributed Scenario 4 shows that costs almost triple from 26.6€ to 73.3€. However, in centralized Scenario 3, costs drop to 17.6€, which is considerably lower. With the dual chamber (Scenario 6), the distributed cost drops to 33€/unit, approaching the cost calculated for centralized Scenario 1. However, it is still considerably higher than the cost calculated for the centralized option (Scenario 5), at 12.6€.

The sensitivity analysis on automation level shows that the cost for the distributed SC Scenario 4 drops from 73.3€ (no automation) to 60.4€ (full automation), which is approximately an 18% cost reduction. This is, however, still considerably more than the 17.6€ per part cost calculated for the centralized Scenario 3 (without automation).

We consider this proposition to be false. Dropping machine prices coupled with improved technology mean that the SC costs of distributed scenarios approach the current (centralized AM SC) costs. These costs are, however, still considerably higher than those associated with comparable technology in centralized scenarios. Automation has a comparable effect – although it has a positive effect on the favorability of the distributed scenarios, the cost of the distributed scenarios continues to be higher than the cost of the centralized scenarios. We note that increasing the automation level is key for the favorability of distributed AM configurations.

Regarding the generalizability of the findings to other contexts, we note that, due to the personalized nature of the surgical guides, the reliability of the SC cannot be compensated for with stock-keeping. This highlights a crucial difference between patient-specific surgical guide SCs (which do not hold inventory) and industrial (spare-parts) SCs, where inventory can compensate for SC interruptions. Therefore, the findings of this research are not (analytically) generalizable (Yin, 2014) to e.g. industrial spare parts SCs where (typically) inventory is held. However, our findings may be transferable to contexts in which inventory is not held, for example the production of other patient-specific medical care products (e.g. molds for implants, splints, and sight models). It is worth noting that this study was carried out in a Dutch context and our findings may be applicable to contexts with similar characteristics, i.e. geographically small areas with a well-developed infrastructure.

The choice between centralized versus distributed configurations is heavily dependent on technological developments and on demand volumes. We therefore have the following recommendations for business practitioners:

- Develop equipment that enables significantly faster production (this includes heating, 3D-printing, and cooling). Furthermore, new equipment should solve the dust-dispersion issue.
- Focus on automating human tasks. These costs will become significant with advancing AM technology, particularly in the distributed scenarios.
- Scale-up to higher volumes, since efficient machine and chamber utilization are key. UMCs can fill the production chamber capacity with products other than surgical guides (e.g. molds for implants, sight models) at almost no additional operational cost.
- Consider alternative SC designs. For instance, a hub configuration where one (or more) UMCs could specialize in the AM of patient-specific products and (cross)

deliver to other UMCs could improve the machine utilization rate and reduce unit cost, while still benefiting from an improved learning loop.
- For UMCs considering the switch from centralized to distributed (in-house) AM, our advice is to wait until technological developments have evolved towards significantly faster AM machines, machines that resolve the dust issue or provide an alternative to SLS techniques.

As with all research, a number of assumptions have been made:

- In the responsiveness calculations, we excluded process wastes (e.g. waiting times) and only used the net time.
- JIT delivery is required by the service provider for the UMCs and problems arise when there are late deliveries. However, we did not take this into account due to the stochastic nature of delivery disruptions and for the sake of simplicity of the model.
- The waiting time for batch completion prior to nesting and production was excluded in the calculations.
- Having to start printing as soon as a trauma order comes in (provided a machine is available) can disturb the service provider workflow, and this comes with additional related costs. This kind of interruption was excluded from our model. Starting production immediately would be a logical operating procedure for distributed scenarios (at the UMCs), significantly improving SC responsiveness.
- The centralized scenarios use subcontracted transportation with a daily pick-up and a 24-hour delivery service according to the shipping agreement. For emergency surgeries (which comprise 20% of the orders), this is unlikely to be optimal, and an immediate pick-up (taxi service straight to the lab bypassing the front desk) could reduce the transportation time to approximately two hours. This may, however, come at a high cost (approximately €200 per order), and was excluded from the calculations.
- According to the contract, delivery of the product should take place within 24h. In reality, the delivery time will often be faster. In our research, however, we specified a 24-hour delivery as the only type of delivery in the centralized scenarios. This has a negative impact on the feasibility of a distributed SC configuration as it eliminates the existence of costly but necessary emergency deliveries.
- Sterilization of the products is required before they can be used in the OR. This is carried out internally in the UMCs (in batches) and can take approximately two hours. We did not include this step in our cost and responsiveness calculations.
- The average weight of the surgical guides is set at 35 g/unit, which creates a raw material cost of 2.3 €/unit. However, AM production cost is heavily dependent on the product volume (Walter et al., 2004). Heavier products require more raw material which will increase the significance of the product weight on the total SC costs.

- The primary focus of our research is on the AM service provider's operational costs; it does not take into account other costs, including e.g. facilities-, management-, marketing-, and systems-related costs.
- Financial benefits may also apply to society at large. The scope of the present study did not include, for example, insurance- and employer-related issues such as the potential reduction in sick days. It is safe to say that the potential integral cost savings that could be achieved by accelerating the learning cycle would more than make up for any additional unit costs associated with the distributed scenario.
- From the UMC side, we did not include potential cost alleviation through a reduction in Operating Room (OR) utilization (at 2750€/h) and number of patient-hospitalization days that may result from an improved learning cycle. It is worth noting that if a decision to change from centralized to distributed AM SC is taken, then, in reality, centralized AM SCs will continue to exist while distributed AM SCs slowly 'fade-in'. In other cases, greenfield situations may exist.
- The UMCs refer to 'speeding-up' the learning loop 'at an acceptable cost' in their objective. These terms are arguably non-specific and hard to measure. We interpreted 'fast enough' as delivered within one working day and 'acceptable costs' as costs that are comparable to the current costs.
- Systems enabling safe and efficient sharing of data files are required. It was not possible to include these elements in our modeling and calculations.
- Both the UMC and AM service provider mentioned other key factors – such as having a 'trusted relationship' – as enabling cooperation towards implementing new SC designs. It was not possible to include this in our modelling.

4.6 Conclusion

The overarching business challenge behind this research is that the UMC would like to achieve faster availability of surgical tools, and would consider the use of in-house AM to improve the learning loop. This article contributes to the limited body of knowledge about the key decision-making factors related to the positioning of centralized versus distributed configurations of AM in a patient-specific medical supply chain.

The findings show that, compared to the current centralized SC configuration, the distributed scenario with soon-available technology halves the delivery time, but costs three times as much. Accelerated delivery of parts – possible because transport is no longer necessary in a distributed SC design – is still too slow to support the fast learning loop that is required. This is due to the long cooling-down time needed to prevent product warping. The high costs are caused by the need to invest in expensive machines at multiple distributed locations as well as the measures that need to be taken in order to prevent dust-dispersion. Both the long cooling and the dust dispersion issues are

caused by the SLS AM technology. Our research suggests that AM technology is not sufficiently mature to disrupt existing supply chains and business models, bringing our findings in line with Rayna and Striukova (2016) and Verboeket and Krikke (2019b). We developed future scenarios based on a fictional machine for which long cooling will no longer be required, and which will have a dual chamber solution, solving the dust dispersion issue. In this scenario, the speed of the distributed SC improves significantly and supports the desired learning loop – at an acceptable cost.

The overall conclusion of our research is that decisions about the configuration of AM SC (centralized versus distributed AM SCs) are strongly interrelated with technological advances. We recommend that future research addresses the integral cost savings resulting from reduced operating room utilization and hospitalization, and the cost benefits to employers and society at large resulting from a faster feedback loop supported by a distributed AM SC configuration. Moreover, we identify a need for further research into alternative designs of distributed AM SCs for patient-specific medical care products in different contexts. Finally, we recommend that research is conducted into the SLS (post) production processes i.e. eliminating dust dispersion and achieving faster cooling processes. With respect to future research, the key parameters that determine the switch from centralized AM to distributed AM are (1) order volume, which is determined by market developments; (2) production speed, (3) equipment costs, and (4) machine and process automation (which are influenced by machine developers and manufacturers).

For decision makers at university hospitals considering a switch from centralized to distributed AM until technology, we recommend waiting until the technology is more advanced in terms of both cost and responsiveness. In addition, efficient machine and chamber utilization is key to making AM a cost-efficient technology and we recommend searching for different AM applications in order increase the order volume.

The authors would like to thank the anonymous sources at the AM service provider and the UMC for their valuable contributions.

Appendix 4.1

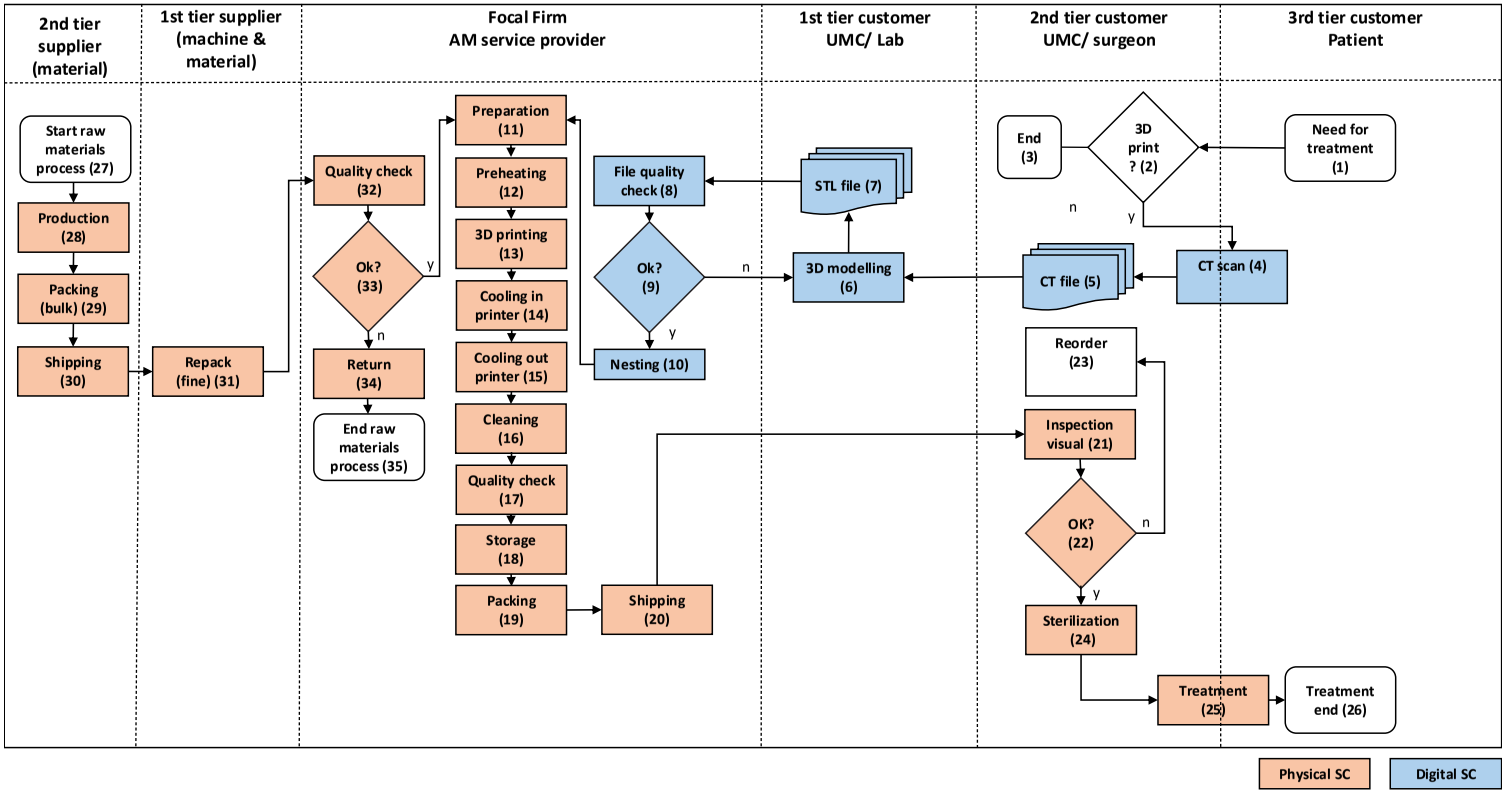


Figure A4.1: Case study: detailed process chain flowchart.

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CHAPTER 5



A case study on introducing additive-manufacturing in traditional orthopedic shoe manufacturing

This article is authored by Victor Verboeket, Harold Krikke, and Mika Salmi. This article was submitted to and rejected by (with the request to resubmit) the international (peer-reviewed) journal 'Journal of Operations Management'.

Abstract

We analyze the cost and lead-time performances of implementing additive-manufacturing (AM) in a traditional orthopedic shoe supply chain (SC) and asses how the effects of AM in a SC can shift from incremental to disruptive.

We gathered real-life data about a traditional-manufacturing SC, and developed future scenarios in which AM is introduced in the SC. Presently, AM can only replace traditional-manufacturing of tools and shoe components at higher total cost. However, with maturing technology, the complete AM production of orthopedic shoes will become feasible in 5-10 years' time. This will induce a disruption of existing SCs, eliminating 70% of the SC steps, improving SC lead-time by 90% and altering SC relations. However, certain thresholds currently prevent disruption. Specifically, the AM of complete orthopedic shoes has to become possible, manufacturing prices have to drop below €630 per pair, and traditional craftsmanship has to be integrated into the digital product design.

This article contributes to the academic knowledge base by pinpointing the conditions for SC disruption by the introduction of AM, and by showing that only the disruptive scenario produces positive results. It also provides guidance for health care policy makers, providers, and insurers for reorganizing their business model and SC.

5.1 Introduction

The world we live in changes at an ever-increasing pace. A digitizing society, sustainability issues, changing consumer behavior and a growing and aging population are all examples of changes that require Supply Chains (SCs) to continuously adapt. A SC can be described as the collection of stakeholders involved in the stream of materials, finances and data from the origin to the user and back. Supply Chain Management is a diffuse domain that overlaps with many other fields – for instance human resource management and information and communication technology. The goal of Supply Chain Management is to create customer value and a competitive advantage (Mentzer et al., 2001). A SC requires a design consisting of decisions about warehousing, manufacturing, transportation modalities, ICT systems, human resources and assortment (Chopra and Meindl, 2013). Traditionally, the performance of a SC is measured in cost and responsiveness (APICS, 2018).

The World Economic Forum refers to the collection of technological developments that are changing society as part of 'the fourth industrial revolution' (Swab, 2017). These developments include robotization, autonomous vehicles, artificial intelligence, augmented reality, big data, block chain and, most relevant to this article, Additive Manufacturing (AM). AM is a group of technologies where material is added layer-by-layer as opposed to subtractive manufacturing where pieces of material are removed from a solid piece (ISO/ASTM, 2015). At present, many different AM applications exist (Maresch and Gartner, 2018), for example, patient-specific healthcare products (the topic of this article).

Healthcare costs in developed countries are high and keep rising. Healthcare spending in the EU jumped from 8.8% in 2008 to 9.6% of GDP in 2017, which is still well below 17.2% spending in the United States (OECD/EU, 2018 p. 134). According to the Dutch Ministry of Health, Welfare and Sport, healthcare costs in the Netherlands are expected to double to 174 billion Euros in 2040 (in comparison to 2015). One third of these projected costs originate in an aging and a growing population, while two thirds can be attributed to other factors – mainly technological advancements – for instance new medicines and equipment (RIVM, 2018). Although technological developments are a major cause of rising health care spending, they also offer an opportunity to reduce costs. In the Netherlands, healthcare expenses are reimbursed by health insurance companies. These insurers stimulate health providers to reduce these costs by reducing the amount that can be reimbursed. This article investigates how implementing AM can reduce healthcare provider SC costs.

We conducted a case study in order to investigate an existing SC and develop future SC scenarios. The case company is a Dutch orthopedic shoe manufacturer that currently uses traditional-manufacturing techniques. Their treatment reimbursement drops 3-5%

yearly which they compensate for by implementing process optimization, for instance by means of standardization and (partial) outsourcing. However, incremental process improvements are limited and other (disruptive) measures are needed. We therefore investigated the impact of implementing AM at various points in the SC. AM production of the complete orthopedic shoe is currently not possible, but AM production of both tools and elements of the shoes is already possible. To obtain an in-depth understanding of the challenges associated with orthopedic shoe manufacturing, we gathered real-life data about the current SC processes. We also gathered information about technological developments in AM in order to develop future scenarios, which we then evaluated in terms of cost and lead-time performance.

Holmström et al. (2016), Verboeket and Krikke (2019b) and Waller and Fawcett (2014) describe the lack of knowledge about the effects of AM on SCs as a gap in the literature that needs to be addressed. This article contributes to the academic knowledge base by pinpointing the thresholds that need to be eliminated in order for the effects of AM in a SC to shift from incremental to disruptive. We also show that disruptive changes are necessary to make a business case for AM in orthopedic shoe production. Our findings will also help decision makers in the patient-specific products industry, health insurance providers and healthcare policy makers to be better prepared by adjusting SC designs, relationships, and remuneration programs while AM technology develops towards maturity.

The next section provides the theoretical foundation, and is followed by the methodology, results, discussion and conclusions.

5.2 Literature review

To ensure a competitive position, a well-designed SC is essential to any business. To establish such a 'winning organization', managers should select the best SC participants, and define the roles and relationships within the SC (Fawcett and Waller, 2014). The SCOR model (APICS, 2018) established a common language for SC professionals and scholars, which has improved the ability to benchmark processes and performances. A SC produces products and services and its performance is measured in terms of a combination of outcomes: cost, responsiveness (lead-time), assets, reliability, flexibility, resilience, security, sustainability and innovation (APICS, 2018, Melnyk et al., 2010). In this research, we assess the traditional outcomes 'cost' and 'lead-time'.

Technological developments incrementally or disruptively influence SCs and force companies to adapt their SC designs (PWC, 2016, Verboeket and Krikke, 2019a). Over the past decade, this has mainly been due to the digitization of SCs. Büyüközkan and Göçer (2018) define a digital SC as 'a smart and value driven process, generating business

with novel (information) technology and analytical processes'. Digitization may disrupt business models and change the game of the actors within the SC (Fawcett and Waller, 2014). For example, more traditional shopping (bricks) has widely been taken-over by internet shopping (clicks). Such digital SCs are likely to require fewer steps – a concept called 'SC disintermediation' (Mills and Camek, 2004) – thus enabling a faster response and requiring less inventory.

One of the technologies digitizing SCs is AM, a cluster of technologies where material is added layer by layer. AM is also known as 3-D printing and, depending on the application, as Rapid Prototyping (RP), Rapid Tooling (RT), and Rapid Manufacturing (RM) (ISO/ASTM, 2015). AM was invented in the 1980s and at first, mainly plastics were used for printing. AM was first commercialized in the early 1990s for the manufacturing of prototypes (RP). With advancing technology, other materials (metal alloys and heat resistant polymers) became 'printable' and, in the late 1990s, AM was also applied for the manufacturing of tools (RT). Once costs had decreased and quality had improved, the manufacturing of final products (RM) became possible in the late 2000s. Rayna and Striukova (2016) now consider RP and RT applications to be 'mature', in contrast to RM applications which are not yet mature.

Today, there are still many problems preventing the roll-out of AM. Verboeket and Krikke (2019b) developed a roadmap specifying the bottlenecks hindering AM from reaching its full potential. Notwithstanding these potential hurdles, many high-quality final product applications do already exist, including the manufacturing of (spare) parts with complex geometries for industrial and aeronautic applications (Atzeni and Salmi, 2012, Gebler et al., 2014, Khajavi et al., 2015), customized consumer products (Bogers et al., 2016, Eyers and Potter, 2015, Maresch and Gartner, 2018), houses (Ford and Despeisse, 2016, Kothman and Faber, 2016, Wagner and Walton, 2016) and patient-specific medical care products, for instance hearing aids, surgical tools and implants (Emelogu et al., 2016, Giannatsis and Dedoussis, 2009, Huang et al., 2013).

The shoe industry has also embraced AM. RP and visual models have been around for many years. RT applications include the manufacture of molds (Chung et al., 2003) and lasts (Amza et al., 2019). Currently, best practices for the AM production of complete shoes can be found in the sports industry. This is driven by a growing customer demand and rising product performance requirements, alongside AM's ability to personalize and manufacture the complex geometries of cushions and supports (Meier et al., 2019). Sports applications include the Adidas Futuregraft (Adidas, 2015) and the New Balance 990 Sport shoe (Forbes, 2019) that use AM for the manufacturing of shoe-elements such as the midsole. Nike uses AM to manufacture the uppers (Dezeen, 2018). Peak sports has manufactured complete shoes by combining powder bed fusion and material extrusion processes (3D_Printing_Industry, 2019). Applications of entirely additively manufactured fashion shoes also exist, although the quality is doubtful (Kim et al.,

2019, Vanderploeg et al., 2017). In the array of patient-specific medical care products, AM of complete orthopedic shoes is not yet possible, but examples of AM produced shoe elements do exist, including insoles (Salles and Gyi, 2013a, Salles and Gyi, 2013b) and orthotics (Jordan, 2019). A high quality digital design is imperative for orthopedic shoes and includes the (3D) geometrical data (foot geometry) and the functional data – for instance modeling of movement and the kind of support needed (Nachtigall et al., 2018). Related to this, Veltink et al. (2003) provide a description of the measuring of movements and Dong et al. (2019) report cases where single material lattice geometry has been simulated using the finite element method and verified with experimental testing for the 3D printing of soles. Unnecessary manufacturing of orthopedic shoes can be avoided by creating simulations using machine learning and big data. Dorschky et al. (2019) describe the use of these kind of simulations for the production of midsoles and suggest that these methods should become more accurate over time.

We used the SCOR categories (APICS, 2018) and the definitions provided by Verboeket and Krikke (2019b) to detail the effects of AM on supply chains and develop SC design propositions to be tested during the empirical phase of this research. We took the current traditional manufacturing SC as the starting point; in the future scenarios, we use AM to replace one or more process steps.

Plan refers to the supply chain configuration decisions that need to be taken when introducing AM. AM may make SCs shorter and simpler (Li et al., 2017, Meisel et al., 2016, Tien, 2012). Moreover, since no product unique tools and know-how are required, and only one kind of raw material is required – which can be delivered on-site prior to design and manufacturing – the traditional design-manufacture-deliver order can change (Petrick and Simpson, 2013). Our first design proposition is:

1. Implementing AM in a traditional-manufacturing SC will make SCs shorter and simpler.

Source includes the supplier-related decisions that need to be taken when introducing AM in SCs. Implementing AM in a traditional-manufacturing SC will affect the suppliers' base. Due to the reduction of SC steps, fewer and different suppliers will be required (Kothman and Faber, 2016). Moreover, strong relationships will be needed with the new and remaining suppliers (De la Torre et al., 2016, Oettmeier and Hofmann, 2016, Petrick and Simpson, 2013). While the relevance of parts suppliers diminishes, the relevance of IT and raw material suppliers increases (Barz et al., 2016, Holmström et al., 2010, Mellor et al., 2014). To prevent high machine investments and high product costs due to inefficient machine usage, demand of single companies – who, by themselves lack sufficient demand – can be bundled by contracting manufacturing out to a 3D printing services supplier (Berman, 2012, Holmström et al., 2010, Holmström and Partanen, 2014). Our second design proposition is:

2. Implementing AM in a traditional-manufacturing SC changes and reduces the need for suppliers. However, strong relationships are needed with the remaining suppliers.

Make includes the manufacturing-related decisions. AM enables complex shaped products to be manufactured in one run, thus reducing the need for assembly. Within the limited physical dimensions, AM machines can produce any desired shape without specific tools, reducing the need for equipment and buildings (Chin, 1998, Chua et al., 2005, Khajavi et al., 2014, Khajavi et al., 2015). Therefore, our third design proposition is:

3. Implementing AM in a traditional-manufacturing SC reduces the need for equipment and buildings.

Although the implementation of AM is a promising way forward, many hurdles still exist: since products are built bit-by-bit, AM is relatively slow compared to traditional mass-manufacturing (Gebler et al., 2014, Wagner and Walton, 2016, Yang and Zhao, 2015). Accordingly, throughputs are low, while machine costs are relatively high (Durach et al., 2017, Dwivedi et al., 2017). Automation levels are low (Ford and Despeisse, 2016, Kothman and Faber, 2016) and the layer-by-layer application of material can results in problems with the mechanical aspects of the product (Ngo et al., 2018). Moreover, manufacturing processes can be unstable and the output unreliable (Durach et al., 2017). Post-processing is necessary to correct the rough product exterior and product sizes are limited to the machine's build envelope (Chekurov et al., 2018, Kretzschmar et al., 2018). These manufacturing issues can cause product quality issues, e.g. inexactness (Berman, 2012, Moore et al., 2016), strength and endurance issues (Chiu and Lin, 2016, Dwivedi et al., 2017), as well as part safety issues (Neely, 2016). These hurdles are included in the 'technical capability evaluation' in Section 5.3.2.2.

Deliver refers to decisions related to storage and distribution. In an AM SC, products are 'digital' until the moment of production. It therefore follows that if manufacturing takes place on-site, and at the moment of consumption, digital storage and distribution will replace physical storage and distribution (Chekurov et al., 2018, Ford and Despeisse, 2016, Holmström et al., 2010). Digital storage of designs requires IT systems, but no physical warehousing (Rogers et al., 2016). Digital distribution requires an IT infrastructure, but easily bypasses physical boundaries. Furthermore, AM products are manufactured from one raw material and raw materials likewise (relatively) easily bypass physical boundaries. Therefore, AM products can reach tough-to-reach locations (e.g. polar areas or war zones), improving SC lead-time (De la Torre et al., 2016, Pérès and Noyes, 2006). Inventory will shift from final products to raw materials (Barz et al., 2016, Eyers and Potter, 2015, Holmström et al., 2016) thus reducing the need for (and cost of) warehouses (Rogers et al., 2016), material handling (Holmström and Partanen, 2014, Huang et al., 2013, Thiesse et al., 2015) and final product inventory. When manufacturing

takes place close to the point of use, transportation requirements reduce (Chen, 2016, Gebler et al., 2014, Steenhuis and Pretorius, 2016). This leads to the fourth proposition:

4. Implementing AM in a traditional-manufacturing SC will shift physical storage and distribution to digital storage and distribution. This reduces the need for material handling and transportation and will, in turn, reduce SC costs and decrease SC lead-time.

Return refers to Closed Loop Supply Chain-related decisions (Krikke et al., 2013). AM only applies material where required. This allows for the manufacturing of hollow constructions which, compared to traditional manufacturing, may reduce raw materials usage between 30% and 60% (Kothman and Faber, 2016, Thiesse et al., 2015). AM can also be used to stretch the product life through (on-site) repair (Ford and Despeisse, 2016). The use of one kind of raw material allows unused material to be reused in subsequent manufacturing cycles. Moreover, AM allows for the use of recycled materials, and reduces emissions, energy use and carbon footprints (Baumers et al., 2013, Chiu and Lin, 2016, Li et al., 2017, Mohr and Khan, 2015, Rylands et al., 2016, Yang and Zhao, 2015). The fifth design proposition is:

5. Implementing AM in a traditional-manufacturing SC reduces the need for raw materials and reduces emissions and carbon footprints.

However, many raw material-related bottlenecks still exist: difficulties in combining various materials (Weller et al., 2015), inadequate material properties (Petrick and Simpson, 2013, Steenhuis and Pretorius, 2016, Wagner and Walton, 2016), high prices (Berman, 2012, Dwivedi et al., 2017, Waller and Fawcett, 2014), and unreliable quality between shipments due to a lack of standardization (Chekurov et al., 2018). Moreover, compared to traditional-manufacturing, a relatively limited amount of different material types exists (Atzeni and Salmi, 2012, Moore et al., 2016, Ngo et al., 2018). This may be caused by the high cost and complexity of material development, although many more materials may come available in the future (Kretzschmar et al., 2018). These bottlenecks are included in the 'technical capability evaluation' in Section 5.3.2.2.

Enable refers to decisions related to IT systems and human resources. Prerequisites for an AM SC are a digital file, a repository for the storage of files, and internet tools that enable co-creation, thus involving customers in the design phase (Bogers et al., 2016, Eyers and Potter, 2015, Holmström et al., 2017, Rylands et al., 2016). Here, protecting the designs from unintended use is a challenge (Rogers et al., 2016) and existing IT infrastructures may not be sufficient to support the transportation of digital files (Chekurov et al., 2018).

Compared to AM – where one machine produces many different shapes – traditional manufacturing requires different techniques, e.g. milling, grinding and drilling. This

means that, when changing to AM, people need to gain new knowledge about AM techniques but require less knowledge about traditional techniques (Mohr and Khan, 2015, Thiesse et al., 2015). Jobs will change and, due to reduced physical handling, less personnel and management may be required (Weller et al., 2015, Emelogu et al., 2016, Khajavi et al., 2014). Our sixth proposition is:

6. Implementing AM in a traditional-manufacturing SC reduces the need for knowledge about traditional techniques, but increases the need for knowledge about AM. Jobs change and fewer personnel are required. Enabling IT systems include digital files and repositories.

A lack of knowledge about designing for AM is considered to be problematic (Durach et al., 2017, Oettmeier and Hofmann, 2016, Thiesse et al., 2015), as outlined in Section 5.3.2.1. Other relevant issues include how clients feel about AM (and whether they provide consent for AM to be used), the absence of machine operators, a potential reluctance to adapt to new work processes, insufficient management back-up, and insufficient confidence in the equipment and raw material suppliers (Durach et al., 2017, Dwivedi et al., 2017).

5.3 Methodology

In line with Kaipia et al. (2017), we combined case study research and design science research (van Aken et al., 2016), also known as intervention-based research. During the case study phase (Section 5.3.1), we studied a problem in its context and collected data about the existing (traditional-manufacturing) SC. In the design science phase (Section 5.3.2), we designed future scenarios where AM (the intervention) is implemented in different degrees in the SC.

5.3.1 Case study

Case study research is a field of investigation that thoroughly researches a phenomenon within its actual context. To ensure research rigor, we followed the instructions provided by Meredith (1998) and Yin (2014) and used logical models and time study maps to analyze the data.

In the Dutch healthcare system, a patient with foot problems is sent to a medical specialist via a general practitioner. The specialist diagnoses the patient and determines the required medical care. After approval of the cost by the health insurance company, patients arrive at our case company, who then provide support soles, orthoses' or orthopedic shoes. Our case company is one of the Dutch market leaders in orthopedic healthcare, established in the early twentieth century. The case company employs 90 full-time equivalents and has a yearly turnover of €10M with five production locations

and 35 sales points spread out over the Netherlands. Orthopedic shoes can vary between those resulting from small adjustments being made to mass-manufactured shoes, to 100% custom made (personalized), hand-made shoes. In our research, we focus on the latter.

Custom made orthopedic shoes are manufactured in five stages (Figure 5.1).



Figure 5.1: Manufacturing stages.

During an initial visit, the feet are scanned and casted to determine the shape and functional specifications. These specifications are used to build a digital shape of the last. The digital file is sent to an external company who produces the wooden last. The last is used as a manufacturing tool in the next stages, which include the manufacturing of the foot bed, fitting shoe, test shoe, and leather outer shell of the final shoe, which is outsourced to East-Asia. Post-manufacturing, the last is stored in a warehouse for future use. During the manufacturing process, the initial design is iteratively improved until the shoe fits well and the patient is satisfied. A detailed SC flow is included in Figure A5.1.1. The health care insurer pays for the first pair of shoes, and three months later for a 2nd (exchange) pair. The useful life of both the first as well as the exchange pair is 15 to 18 months, after which patients may request new pairs. Our research is limited to the first-time delivery of a pair of shoes.

As a result of rapidly rising healthcare costs, health care insurers reduce the remuneration every year. The case company has been forced to compensate for the income loss by cutting costs, for instance by implementing process standardization and outsourcing parts of the manufacturing process to countries which provide cheap labor, which has increased the order lead-time. The case company understands that the remuneration reductions will not stop while also recognizing that traditional cost-cutting options are reaching an end. They will need to reinvent their business model in order to survive, and envision a future where they can maintain their good patient relations and in-depth knowledge about treatment of foot problems while outsourcing all manufacturing activities. The aim of this research is to find out the role AM has to play in this envisioned future.

For the data collection, we followed the guidelines provided by Yin (2014) by drawing up the (current) supply chain processes and gathering volume, lead-time and cost information for each process step. This data was processed in a spreadsheet program. Table 5.1 presents the data sources.

Table 5.1: Data sources

Company	Position	Role
Orthopedic shoe manufacturer	CEO	- Provide and verify current process flow and data; - In cooperation with researcher, develop future SC processes; - Verify future scenarios and assumptions; - Provide digital design feasibility data
	Operations manager	- Verify current processes and data and future scenarios
	Digital design specialist	- Verify future scenarios; - Provide digital design feasibility data
3D printing service supplier	CEO	- Verify future scenarios; - Provide AM cost data on future scenarios; - Provide future AM feasibility data

5.3.2 Scenarios

Scenario analysis (Varum and Melo, 2010) is considered to be a helpful method that can be used to create and rationalize upcoming opportunities (Cornelius et al., 2005). Sodhi (2003) mentions three phases in strategic SC planning - namely designing, calculating and validating the scenarios. These steps are explained next.

The base case (Scenario 0) consists of the current SC (traditional-manufacturing) processes. The future scenarios differ in terms of two variables: (1) AM increasingly penetrating the SC, and (2) future developments in advancing AM technology (enhancing quality) and advancing IT (enhancing further digitization of the product design).

5.3.2.1 AM increasingly penetrating the SC

The first author and the orthopedic shoe manufacturer co-created the scenarios which were iteratively improved until a consensus was reached. The changes included the addition and deletion of process steps to reflect the reality of the situation.

Table 5.2 explains the future scenario where AM increasingly penetrates the SC.

Table 5.2: Scenarios

Name	Description	Detailed processes in Appendix 5.1, Figure
0. Current (base case)	All process steps are traditional-manufacturing	A5.1.1
1. AM of the last	AM production replaces traditional manufacturing of the last	A5.1.2
2. AM of the foot bed	AM production replaces traditional manufacturing of the last and the foot bed	A5.1.3
3. AM of the fitting shoe	AM production replaces traditional manufacturing of the last, the foot bed and the fitting shoe	A5.1.4
4a. AM of the test shoe (including fitting process)	AM production replaces traditional manufacturing of the last, the foot bed, the fitting and the test shoe. The 'fitting iterations' continue to take place	A5.1.5
4b. AM of the test shoe (excluding fitting process)	AM production replaces traditional manufacturing of the last, the foot bed and the test shoe. The 'fitting iterations (fitting shoe)' are eliminated	A5.1.6
5. AM of the final shoe	AM production of the complete final shoe; traditional-manufacturing of the last, the foot bed, the fitting, test and the final shoe are eliminated	A5.1.7

Introducing AM in the chain does not automatically eliminate components (or tools) upstream. For instance, when the fitting shoe is AM produced (Scenario 3), the last and foot bed are still required. It is also worth noting that the current design is imperfect and the final product is created through 'fitting' iterations. However, a 'perfect' digital design is a prerequisite as input for AM since iterations to AM products are either complicated or impossible. We therefore developed scenarios including the 'fitting' iteration process (Scenarios 0 through 4a) and excluding the fitting iteration process (Scenarios 4b and 5).

Outsourcing AM to 3D printing service suppliers is a common practice for companies who, by themselves, lack the economies of scale to invest in AM. Since the case companies' volumes are limited (1500 pairs/year), we used outsourced AM in the modelling. We obtained data from one of the leading 3D printing suppliers located in the Netherlands who uses the powder bed fusion process for polyamide material and serves as an intermediary for other AM techniques. The company's CEO is our data source (see Table 5.1). He is very well informed about the AM market due to the fact that he has held this position for over 6 years.

5.3.2.2 The future developments in advancing AM and digitization

The scenarios in Table 5.2 will become valid once technology has sufficiently matured – which will happen once the hurdles that prevent the roll-out of AM have been resolved

(Verboeket and Krikke, 2019b). In line with Jiang et al. (2017) – who create scenarios using AM in 2030 – we took a current (2020) mid- (2025) and long-term view (2030) in each scenario, in order to determine to what extent these hurdles are expected to be solved at each of these time points. We clustered the hurdles mentioned in Section 2 into: (a) AM technical hurdles, (b) AM cost developments, and (c) digital design hurdles.

(a) AM technical hurdles include: the fact that it is hard to combine various materials; inadequate material properties; inconsistent quality between shipments; a limited amount of different material types; slow AM; low throughputs; required post-processing; limited product sizes; unstable and untrustworthy manufacturing processes; poor mechanical characteristics; inexact products; rough surface; insufficient strength & endurance, and parts safety issues.

To assess the technical feasibility of AM production in the various scenarios, taking into account the aforementioned hurdles, we developed a 7-point Likert scale (Likert, 1932) which was completed by the 3D-printing supplier (who has expertise in this area). The results are outlined in Table A5.2.1. At present, AM production of the test and final shoe is not considered possible. Therefore, for the remainder of this article, we excluded Scenarios 4a, 4b, and 5 in 2020, yet included these scenarios in 2025 and 2030.

(b) AM cost barriers are due in particular to high raw material and machining costs. We requested the 3D-printing suppliers' expert opinion about future developments in terms of cost estimates of AM components, see Table A5.2.2, and used this information in the scenario calculations. The robustness of the AM cost modelling was checked by conducting a sensitivity analysis (see Section 5.4.4).

(c) To assess the feasibility of digital design in the various scenarios, bearing in mind the lack of knowledge in this area, we constructed a 7-point Likert scale (Likert, 1932) which was completed by the CEO of the case company and a digital design specialist. A digital design includes the geometrical and functional information, e.g. the support positioning (hard elements) and comfortable positioning (soft elements). We projected a 95-98% first time right. As the results in Table A5.2.3 show, digital design knowledge is likely possible in 2020 and will mature such that it will definitely be possible in 2030. We therefore included all scenarios for further analysis.

5.3.2.3 Calculations

We calculated the cost for the manufacture of one pair of shoes and used the cost, lead-time and volume required for each SC step. In line with the total SC management costs (APICS, 2018), we also included the costs for AM production, transportation, outsourcing, materials, human resources, facilities and equipment.

The availability of equipment and facilities was set at 2000 hours/year, and for human resources at 1200 h/year. We used the company's internal accountancy data, e.g. the

depreciation periods, or, in instances where equipment was leased, the monthly lease rates. If equipment is only used for the orthopedic shoes, the costs were determined by dividing the yearly cost by the yearly order volume. Similarly, the facility costs were based on the m2 cost and time used. Facilities are assumed to be leased and include the costs for cleaning, heating, lighting and basic interior. Material and outsourcing costs were calculated based on the CEO's informed estimates. The equipment, facilities and HR are assumed to be available for other tasks, unrelated to orthopedic shoes. The 'smart' design software cost is set at 10,000€/y.

Note that scenario costs are intended to be used for scenario comparison. The 'real' costs would be approximately 50% higher, since our calculation model excludes the costs for overheads, financing, under-utilized equipment, human resources and machines, as well as failure costs.

For the SC lead-time calculation, we also used the SC process flows. The process flows, data, scenarios and assumptions were verified by the field experts (Table 5.1). All calculations were verified by the third author.

5.4 Results

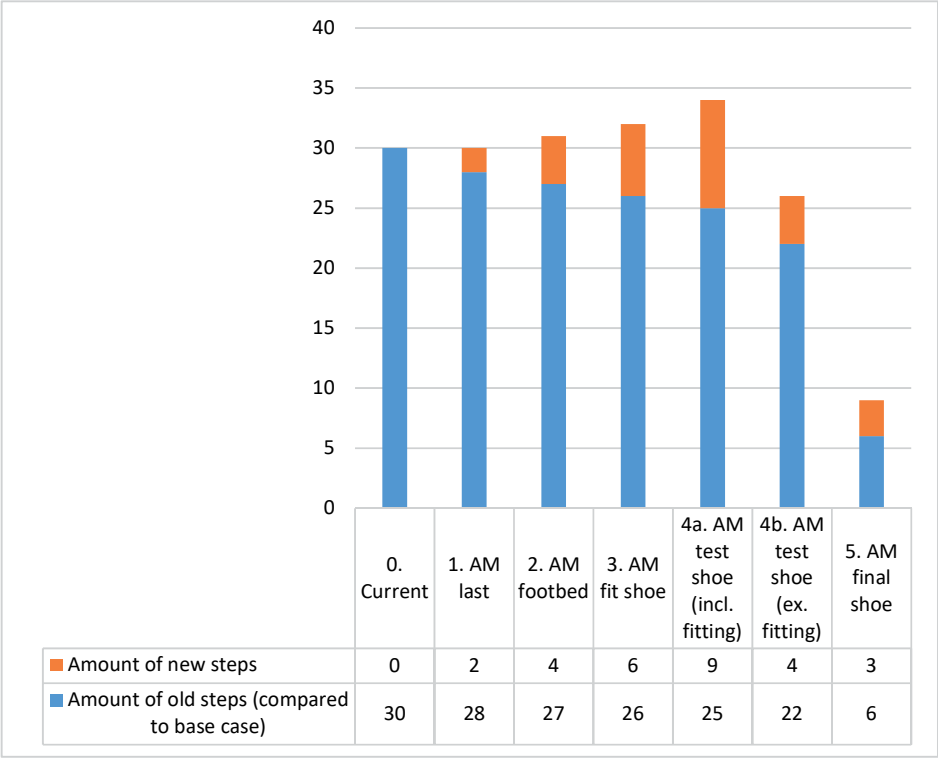
In this section, the codes [p_number] indicate the related design propositions.

5.4.1 SC process steps analysis

Figure 5.2 shows the added and deleted process steps.

In **Scenarios 1 through 4a**, some 'old' traditional-manufacturing steps are replaced by 'new' AM steps, hence the need for (traditional) knowledge [p6], equipment and facilities [p3] reduces. The number of process steps increases due to the addition of digital modification steps for each component which require IT tools and AM design knowledge [p6]. With the decrease of traditionally-manufactured components, fewer (traditional) raw materials and parts suppliers are needed [p5]. Outsourced traditional last-manufacturing is replaced by outsourced AM [p2]. The shipping transactions increase from four (base case) to five (Scenario 4a) [p5]. Physical storage of the lasts is still required [p4].

In **Scenario 4b**, the number of process steps decreases from 34 (Scenario 4a) to 26, due to the elimination of the fitting shoe, footbed, and related digital modification, transportation [p4] and corrections. Raw materials for the fitting shoe are unnecessary [p5] and, compared to Scenario 4a, no changes are needed in relation to knowledge, IT design tools [p6], equipment, facilities [p3] and suppliers relations [p2].



	0. Current	1. AM last	2. AM footbed	3. AM fit shoe	4a. AM test shoe (incl. fitting)	4b. AM test shoe (ex. fitting)	5. AM final shoe
Amount of new steps	0	2	4	6	9	4	3
Amount of old steps (compared to base case)	30	28	27	26	25	22	6

Figure 5.2: Number of steps in each scenario.

Due to the elimination of all upstream tools and components, **Scenario 5** (complete shoe AM) shows a 70% reduction in the number of SC process steps (compared to base case), making the SC much simpler and shorter [p1]. Except for the foot specialist room, no specific facilities are required [p3]. No traditional-manufacturing machines and tools are required, as these are replaced by one (outsourced) AM machine [p3]. The number of suppliers reduces from six (base case) to two [p2] which suggests an increased dependency on the 3D printing supplier [p2]. The material handling activities reduce, and transportation steps reduce from four (base case) to one [p4]. Moreover, since all transportation takes place in the Netherlands, the related emissions and carbon footprints are likely to decrease [p5]. Dependency on the digital design – including the required IT systems and associated knowledge [p6] – increases since the quality-improvement iterations are eliminated.

5.4.2 Cost and lead-time analysis

Figure 5.3 shows the SC cost and lead-time performances.



	0. Current	1. AM last	2. AM footbed	3. AM fit shoe	4a. AM test shoe (incl. fitting)	4b. AM test shoe (ex. fitting)	5. AM final shoe
2020 costs [€]	908	1036	1135	1428			
2025 costs [€]	908	949	1019	1239	1701	1282	1364
2030 costs [€]	908	927	990	1138	1418	1079	1002
Lead-time [h]	466	466	465	465	512	486	53

Figure 5.3: Cost and lead-time results.

The SC lead-time is identical in 2020, 2025 and 2030. For Scenarios 0, 1, 2 and 3, the lead-time is comparable, due to the fact that the AM production and transportation time of the last, foot bed and fitting shoe is comparable to that of traditional-manufacturing. The lead-time increase in Scenario 4a is due slower AM production (24 hours) and transportation (24 hours) as compared to the faster traditional-manufacturing (11 hours) without transportation. Scenario 4b is slightly faster than 4a, which is mainly due to reduced transportation. In Scenario 5, the SC lead-time decreases by about 90% as compared to Scenario 0, due to the elimination of 70% of the SC process steps [p4]. A key contributor of the SC lead-time in Scenarios 0-4b is the outsourced traditional manufacturing of the outer shell to an East-Asian partner, which takes 360 hours. Alternatively, outsourcing to a geographically closer supplier (which is possible in all Scenarios 0 through 4b) can reduce this to approximately 120 hours. In that case, the lead-time improvement of Scenario 5 would still be 77%, as compared to base case.

Compared to base case, in 2020 none of the AM scenarios are cost competitive. In 2025, only Scenario 1 is cost competitive. In 2030, Scenario 1 improves the cost performance by €15, and in Scenario 5 by 131€ [p4].

Note that in Scenario 4b, the 'fitting process steps' are eliminated. The costs attributed to the fitting process ((cost Scenario 4a) – (cost Scenario 4b)) are €327 (2025) and €272 (2030). Nevertheless, the costs attributed to the fitting process in traditional-manufacturing are approximately €60 (steps 8 through 11, see Appendix 5.1). The

difference between €327/€272 and €60 is explained by the fact that AM of the test shoe allows for elimination of the fitting shoe and footbed, whilst in traditional-manufacturing these steps are still needed. Elimination of these fitting process steps is only possible if a high quality design exists. The €131 cost reduction in Scenario 5 is therefore attributed to both introducing AM in a traditional SC, as well as introducing the (high quality) digital design. Therefore, the lack of a high quality design can therefore be seen as a threshold currently preventing the effective implementation of AM.

5.4.3 Cost components

Figure 5.4 shows the cost breakdown in various categories.

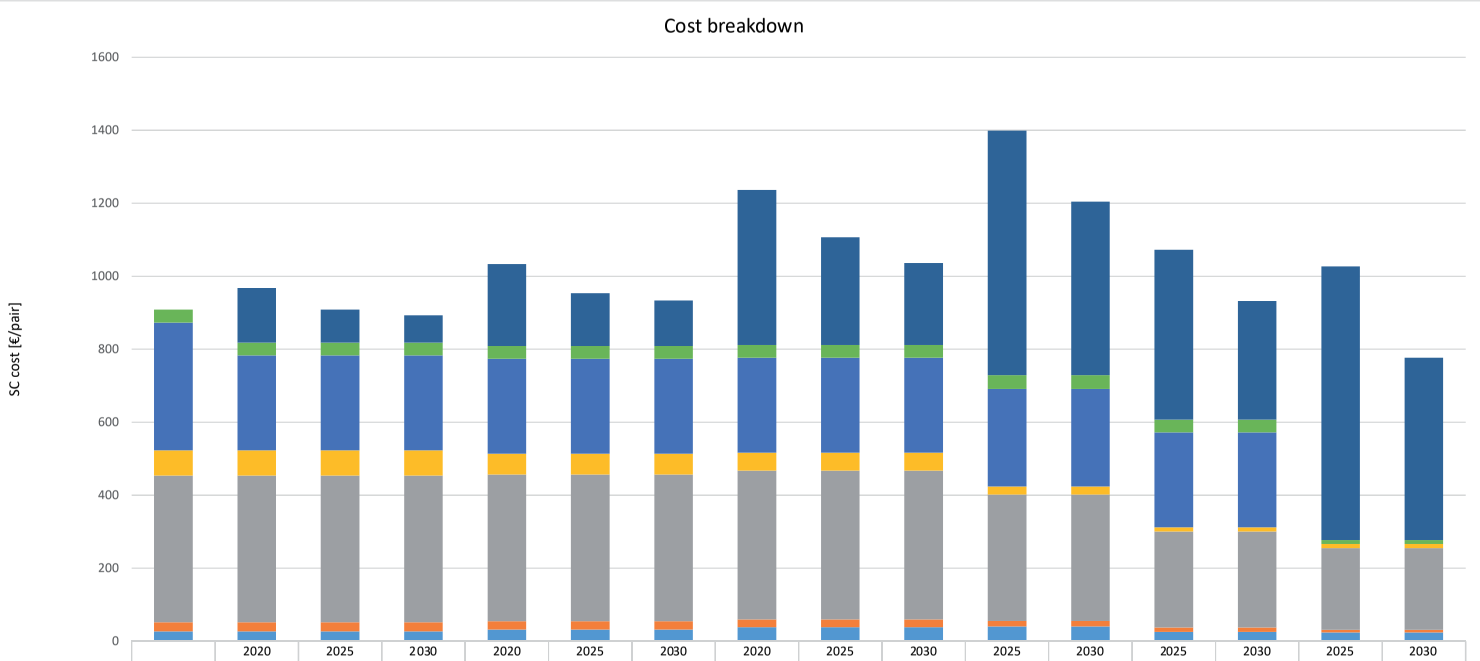
In Figure 5.4, **AM** represents the cumulated AM production costs. Obviously, since more components are AM produced in Scenarios 1 to 5, the costs attributed to AM rise. In 2030, two-third of the SC costs are attributed to AM, indicating an increased dependency on the 3D printing supplier [p2]. Since the AM component costs are predicted to decrease in 2025 and 2030 (Table A2.1), the AM cost portion drops over time.

Outsourced includes the outsourced traditional manufacturing costs of the last and the outer shell. Compared to base case, these costs drop in the other scenarios due to the elimination of traditional-manufacturing of the last and the outer shell, thus reducing the dependency on these suppliers [p2].

Transportation relates to the transportation costs. Scenario 4a includes an additional transportation step making the cost slightly higher than in the other scenarios. The cost drops to €10 in Scenario 5 [p4], indicating a reduction of transportation related emissions and carbon footprints [p5].

Material costs includes the raw materials costs for the cast, foot bed, fitting and test shoe. The costs reduce with the increasing penetration of AM, indicating a reduced need for warehousing and inventory of raw materials [p4, p5]. The remaining material costs in Scenarios 4b and 5 are related to the cast. The AM raw material costs are an integral part of the AM category.

Human Resources costs relate to the foot specialists, machine operators and digital designers. In Scenarios 2 and 3, these costs are comparable, but the focus shifts away from machine operators to digital designers. Scenario 4a requires less test shoe machine operators, but more test shoe digital designers. The cost drop in Scenario 4b is due to the elimination of fitting tasks (foot specialists) and corrections (machine operators). Scenario 5 costs consist of costs related to foot specialists and digital designers [p6].



	0. Current	1. AM last			2. AM footbed			3. AM fit shoe			4a. AM test shoe (incl. fitting)		4b. AM test shoe (ex. fitting)		5. AM final shoe	
		2020	2025	2030	2020	2025	2030	2020	2025	2030	2025	2030	2025	2030	2025	2030
AM	0	150	90	75	225	145	125	425	295	225	670	475	465	325	750	500
Transportation	35	35	35	35	35	35	35	35	35	35	38	38	35	35	10	10
Outsourced	350	260	260	260	260	260	260	260	260	260	268	268	260	260	0	0
Material	69	69	69	69	57	57	57	49	49	49	22	22	12	12	12	12
Human Resources	402	402	402	402	402	402	402	408	408	408	346	346	263	263	224	224
Facility	25	25	25	25	23	23	23	21	21	21	15	15	12	12	7	7
Equipment	27	27	27	27	32	32	32	38	38	38	40	40	25	25	24	24

Figure 5.4: Cost breakdown of the scenarios.

Facility costs include those of treatment and digital designer rooms, production cells and logistic operations. Due to the elimination of production activities, the cost of production cells reduces in Scenarios 2, 3 and 4a, and diminishes further still in Scenario 4b (due to a reduced need for treatment rooms and corrections in production cells). The cost of Scenario 5 consists of treatment and digital designer room costs [p3].

Equipment costs encompass IT and production equipment costs. The increase in Scenarios 2, 3 and 4a is due to the new smart design software [p6], although fewer grinding and vacuum machines, presses and ovens [p3] are required. Scenario 4b requires less smart design software (for the foot bed and fitting shoe), production machines (reduced rework), and tables and software (reduced fitting). The cost of Scenario 5 consists of IT hardware and (smart design) software costs [p3, p6].

5.4.4 Sensitivity analysis

The future AM costs (Table A5.2.2) are forecasts and should be treated with caution. Moreover, it should be noted that with the increasing penetration of AM, the costs attributed to AM increase. We therefore checked the robustness of the AM cost modelling by conducting a sensitivity analysis on AM costs elasticity, see Appendix 5.3. Table 5.3 sets out the minimal percentages by which the (estimated) AM production costs have to drop in order for the total SC costs to be competitive with the base case scenario. In effect, this means that the total SC costs have to drop below €908.

Table 5.3: Cost competitiveness

	Years		
Scenario	**2020**	**2025**	**2030**
1. AM last	<60%	<100%	<120%
2. AM foot bed	<44%	<68%	<79%
3. AM fitting shoe	<22%	<32%	<43%
4a. AM test shoe (including fitting)	N/A	<26%	<37%
4b. AM test shoe (excluding fitting)	N/A	<64%	<92%
5. AM final shoe	N/A	<84%	<126%

If the AM cost for the last (Scenario 1) drops to €90 – expected in 2025 –, AM becomes cost competitive with traditional-manufacturing. AM of the last and foot bed (Scenario 2) may become cost competitive with traditional-manufacturing if the AM cost drops below 68% - 79%. The required AM cost drops in Scenarios 3 and 4a are significant (22% - 43%), and are not, we feel, realistically achievable. AM of the test shoe (Scenario 4b) may become cost competitive with traditional-manufacturing if the AM cost drops to 64% - 92%. AM of the complete shoe (Scenario 5) becomes cost competitive if the AM

production cost drops below €630 per pair of shoes which – according to the authors – should become feasible in 2030.

5.5 Discussion

The benefits of **Scenario 1** seem limited. The cost performance is competitive with base case when the AM last production cost drops below €90. However, the digital design is currently imperfect and while corrections to a (traditional) wooden last are made easily, it is unclear how this would work with an AM produced last. The advantages of **Scenario 2** also appear doubtful. The SC costs may become cost competitive if AM manufacturing costs drop. However, traditionally-manufactured foot beds are iteratively adjusted to the patient needs, and such alterations may be more difficult to achieve using AM. Achieving (cost) benefits with **Scenario 3** also appears unrealistic. Moreover, a new fitting shoe can be quickly traditionally-manufactured in-house while AM is slower. **Scenario 4a** worsens SC performance. In addition, the correction of traditionally-manufactured test shoes involves skilled craftsmanship, and this will be absent when using AM. Although **Scenario 4b** may become cost competitive with the base case, it presents extensive risks, since there is a high dependency on the availability of a 'perfect' digital design. Finally, the benefits – and risks – associated with **Scenario 5** are great. The SC costs appear to be competitive with traditional-manufacturing costs, while the lead-time improvement is tremendous. The existing roles, relations, facilities, and tools change completely, i.e. the SC is disrupted. The role of the orthopedic shoe manufacturer changes to that of process-orchestrator. Here, the shoe manufacturer brings added value by translating their specialist knowledge about foot treatment into a 'perfect' digital design, supported by IT systems. However, the immaturity of both AM production and digital design pose significant business risks.

Implementing AM in the SC in Scenarios 1 to 4b merely causes incremental effects whilst also introducing uncertainties, and is only competitive if AM costs drop significantly. In contrast, in Scenario 5, AM causes disruptive effects and may significantly improve SC performance, thus outweighing the potential risks. Our analysis shows that disruption depends on the ability of AM to produce high quality orthopedic shoes (at acceptable costs), but also on the ability to create high quality ('perfect') digital designs, since the costs associated with the trial and error quality-optimization procedures need to be eliminated. Related to this, a key challenge will be the digitization of the shoemaker's craftsmanship. For this purpose, we envision IT tools and historical databases applying data analytics to uncover analytical relationships instead of causal relationships (Waller and Fawcett, 2013). Figure 5.5 depicts the evolution of the various scenarios.

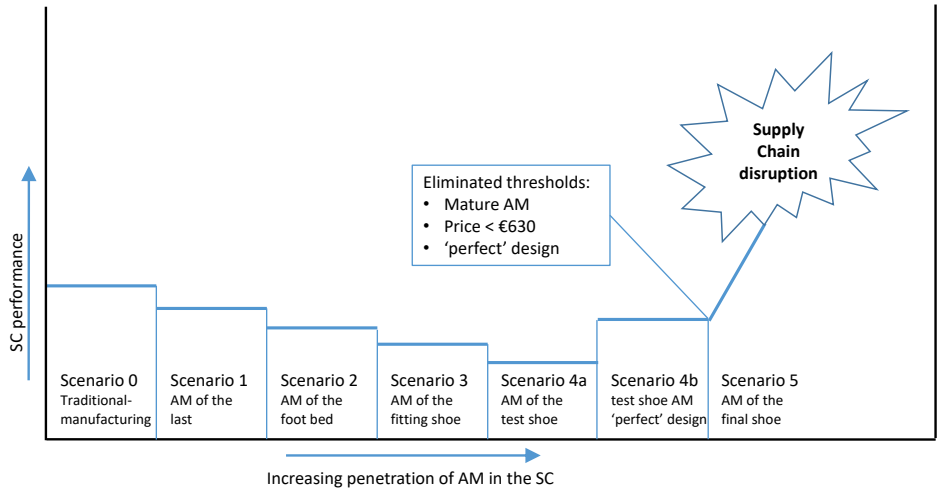


Figure 5.5: From incremental to disruptive SC change.

Evaluation of the design propositions:

1. Implementing AM in a traditional-manufacturing SC will make SCs shorter and simpler.

Proposition 1 is **untrue for Scenarios 1, 2, 3, 4a and 4b**. The traditional-manufacturing steps are replaced by AM production steps, and steps are added for digital modification, hence the total amount of steps increases. Although the amount of process steps decreases in Scenario 4b, the elimination of the fitting steps is attributed to the 'perfect' digital design, and not to the implementation of AM. In contrast, Proposition 1 is **true for Scenario 5**. Compared to base case, there is a 70% reduction of the SC process steps, making the SC much simpler and shorter.

2. Implementing AM in a traditional-manufacturing SC changes and reduces the need for suppliers. However, strong relationships are needed with the remaining suppliers.

Proposition 2 is **true for all scenarios**. With the rising penetration of AM, fewer components are traditionally manufactured in-house, hence the need for (in-house) raw materials – and therefore the need for those suppliers – reduces. They are replaced by one 3D printing services supplier and new IT software suppliers. The traditional supplier base further reduces in Scenario 5, while dependency on the 3D printing and IT suppliers further increases.

3. Implementing AM in a traditional-manufacturing SC reduces the need for equipment and buildings.

Proposition 3 is **true for all scenarios**. With the increasing penetration of AM, fewer production machines (and less space) are required. Fewer machines and facilities are needed at the 3D printing supplier.

4. Implementing AM in a traditional-manufacturing SC will shift physical storage and distribution to digital storage and distribution. This reduces the need for material handling and transportation and will, in turn, reduce SC costs and decrease SC lead-time.

Proposition 4 is **untrue for Scenarios 1 to 4b**. In these scenarios, the traditional-manufacturing material handling and transportation activities are replaced by similar AM tasks while the SC cost and lead-time performances worsen. Moreover, the eliminated steps of Scenario 4b are not attributed to the introduction of AM, but rather to the digital design. In contrast, Proposition 4 is **true for Scenario 5**. Here, it is likely that AM production becomes cost competitive with traditional-manufacturing. The material handling and transportation activities reduce and the SC lead-time improves significantly.

5. Implementing AM in a traditional-manufacturing SC reduces the need for raw materials and reduces emissions and carbon footprints.

Proposition 5 is **untrue for Scenarios 1, 2, 3 and 4a**. Although less raw materials are used for traditional-manufacturing, more raw materials are required for AM production. The amount of shipping transactions (and consequently emissions and footprints) stay the same at 4, and even increase to 5 in Scenario 4a. Proposition 5 is **partly true for Scenario 4b** since, compared to Scenario 4a, the need for raw materials for the fitting shoe reduces. Proposition 5 is **true for Scenario 5**. Since the final shoe is manufactured in one run, raw materials for the last and components are not required. Transportation (along with the related emissions and carbon footprints) reduces. Note that our analysis does not include the entire SC footprint of raw materials and emissions which depend on the chosen AM technology.

6. Implementing AM in a traditional-manufacturing SC reduces the need for knowledge about traditional techniques, but increases the need for knowledge about AM. Jobs change and fewer personnel are required. Enabling IT systems include digital files and repositories.

Proposition 6 is **true for all scenarios**. As AM increasingly penetrates the SC, 'old' traditional-manufacturing steps are replaced by 'new' AM step thus reducing the need for (traditional) knowledge. The eliminated processes are replaced by new digital modification steps requiring staff with AM design knowledge and IT tools. Elimination of the costly fitting process in Scenario 4b and 5 requires investments in smart software able to analyze large amounts of data.

5.6 Conclusions, limitations and recommendations

The societal issue driving this research is the rise of healthcare costs, and the belief that innovative technology can help in designing financially sustainable healthcare. We investigated the effects of introducing AM in a traditional-manufacturing orthopedic shoe SC and found that incremental and disruptive effects are possible. Incremental effects appear when AM is introduced for the production of tools and components. Unexpectedly, this increases the amount of SC steps and has negative cost and lead-time effects. Disruptive effects appear when AM of the final shoes becomes possible, which is expected to be in five to ten years' time from now. In this scenario, 70% of the SC steps become redundant and lead-time decreases by 90%. For this to work, a 'perfect' digital design is required, and AM (outsourced) production costs need to drop below €630 per pair. In line with this, we suggest the need for research into how traditional craftsmanship can be embedded into digital designs and envision uncovering analytical relationships in patient data. We acknowledge that total SC costs would be significantly higher than the AM production cost of €630, and reiterate that our calculation model excluded indirect costs. In line with Durach et al. (2017) – who indicate that customers' perception of AM is relevant, alongside issues of consent – we also recommend research into patient acceptance of 3D printed shoes.

When considering the implementation of AM in a traditional-manufacturing SC, the results of this research are transferable to geographic areas beyond the Netherlands. They are also relevant in other contexts with comparable characteristics – i.e. the manufacture of personalized products.

The academic world benefits from our research since we pinpoint the conditions for SC disruption and the importance of disruptive innovations. A major finding of this research is that merely introducing AM is not sufficient for SC performance improvement. Within the orthopedic shoe context, we demonstrate that digitizing supply chains is only beneficial if both AM as well as high quality digital designs are implemented. In line with Mandolla et al. (2019) – who combine AM and blockchain – a digital twin of AM and data analytics is required in order to achieve the desired benefits. Health care providers – orthopedic shoe manufacturers in particular – will benefit from our results by gaining a more comprehensive understanding of the required business model adjustments. Healthcare policy makers and insurers will benefit from this research by gaining an understanding of how AM can support the design of sustainable healthcare systems once technology has sufficiently matured.

The authors would like to thank the anonymous sources at the orthopedic shoe manufacturer and the 3D printing service supplier for their valuable contributions.

Appendix 5.1

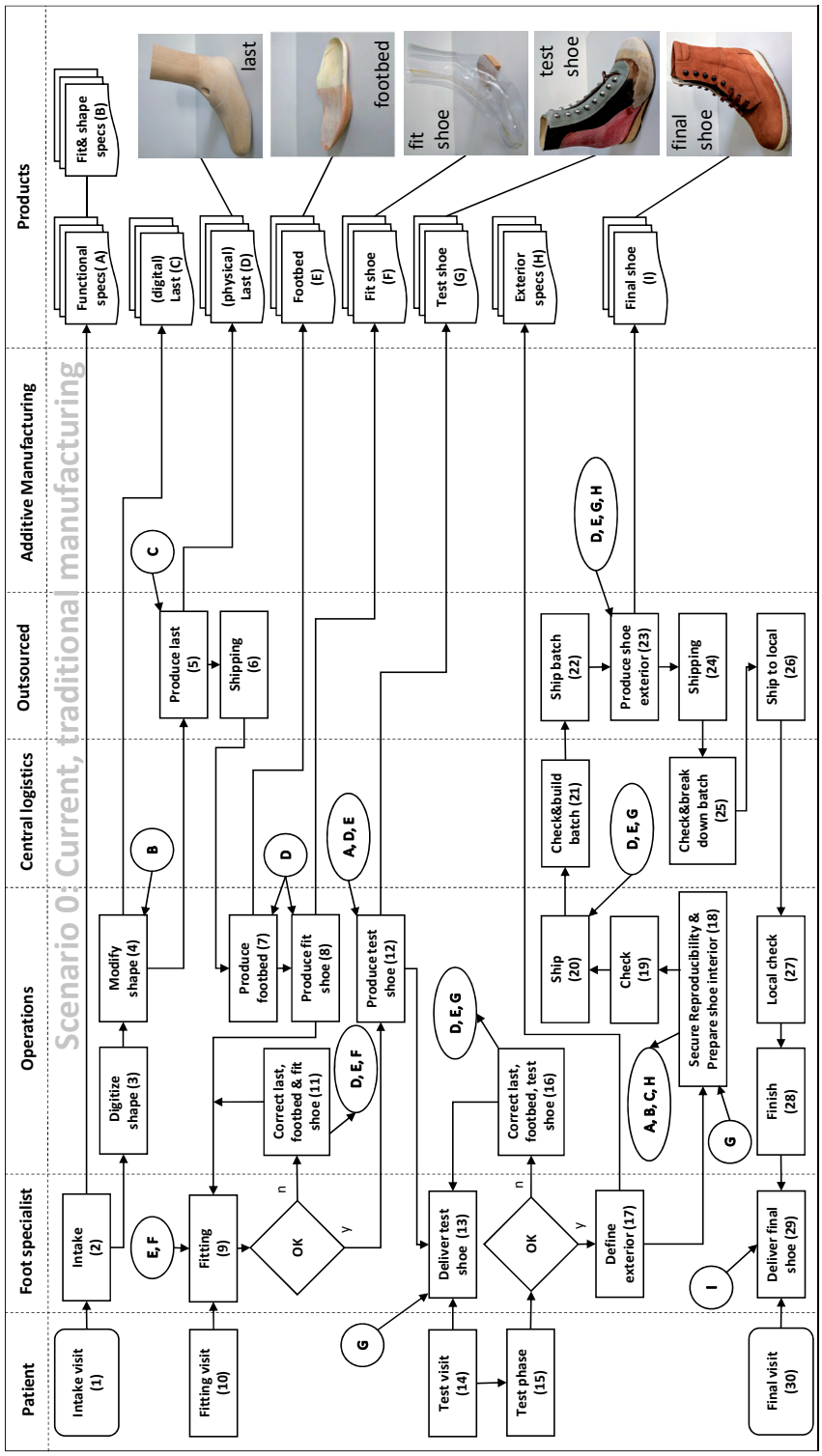


Figure A5.1.1: Current process flow.

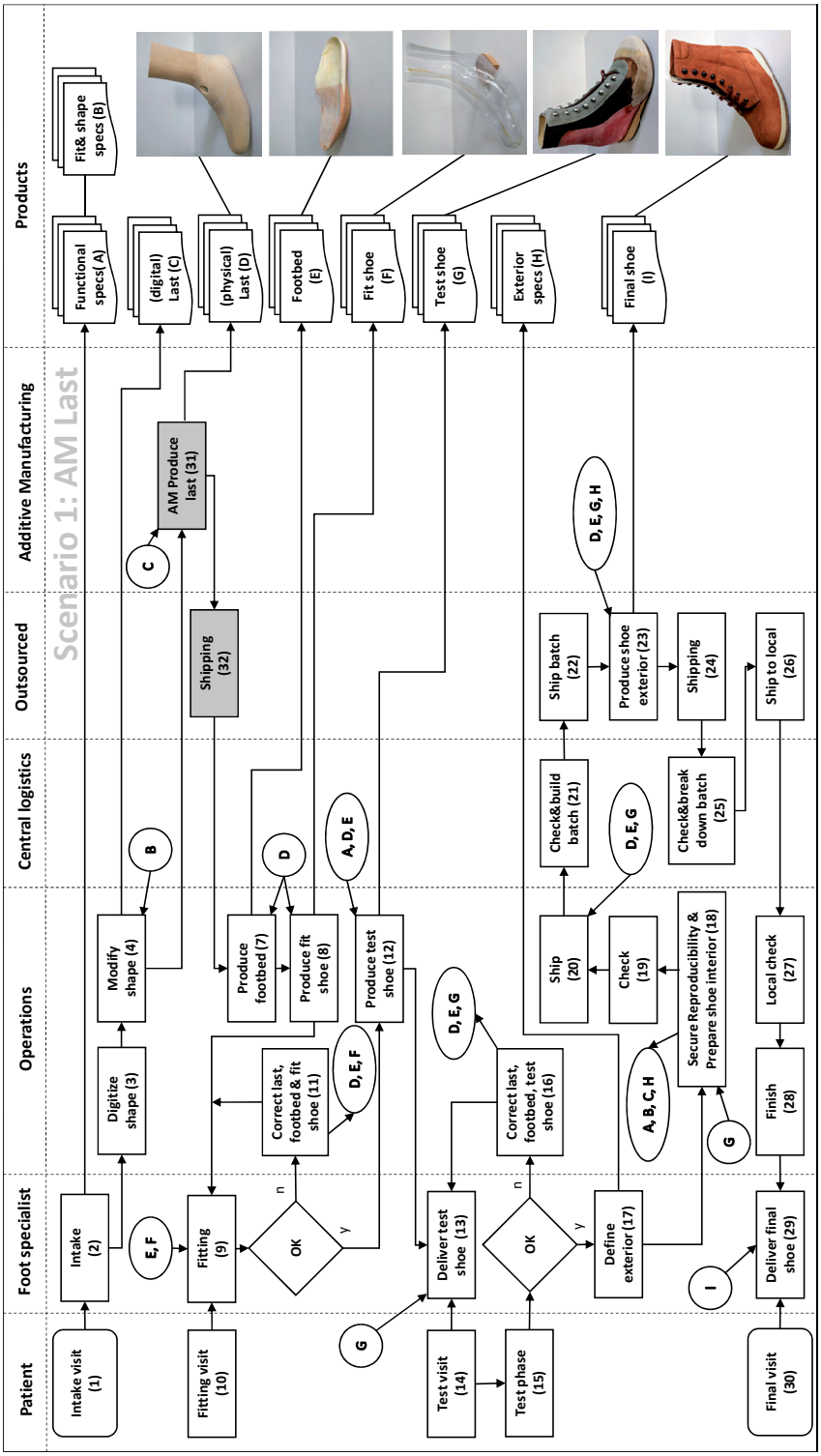


Figure A5.1.2: Process flow Scenario 1.

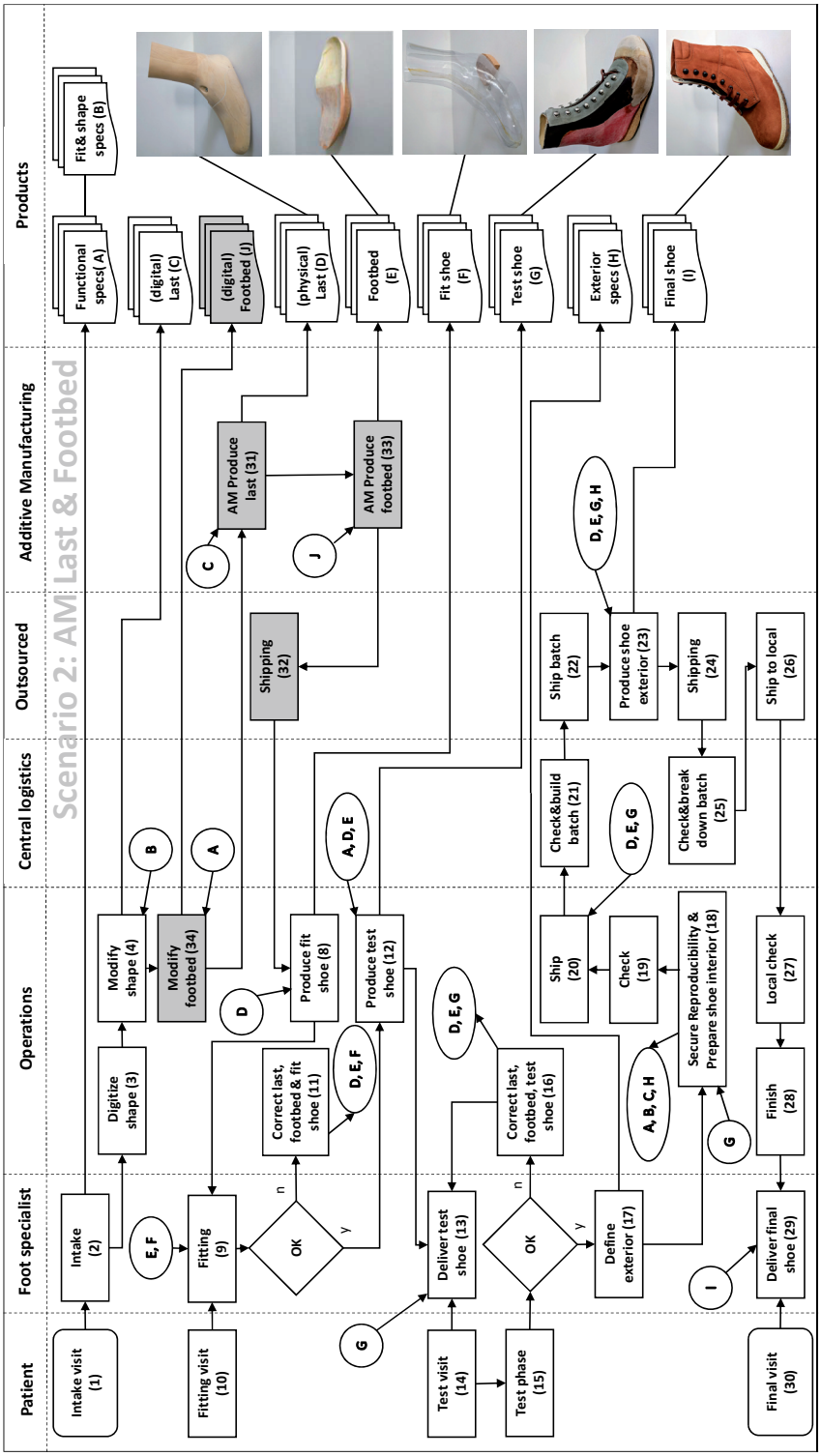


Figure A5.1.3: Process flow Scenario 2.

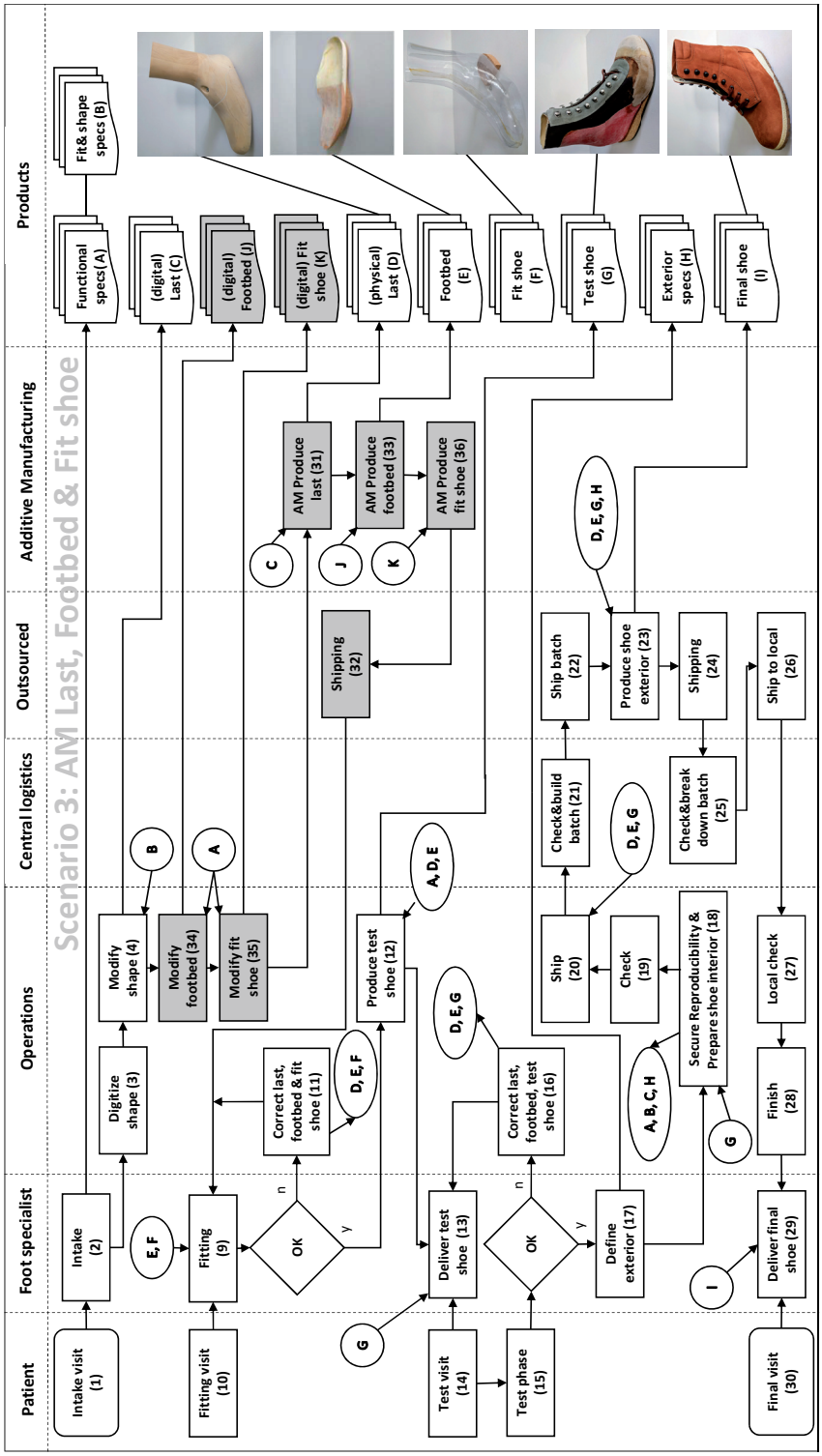


Figure A5.1.4: Scenario 3.

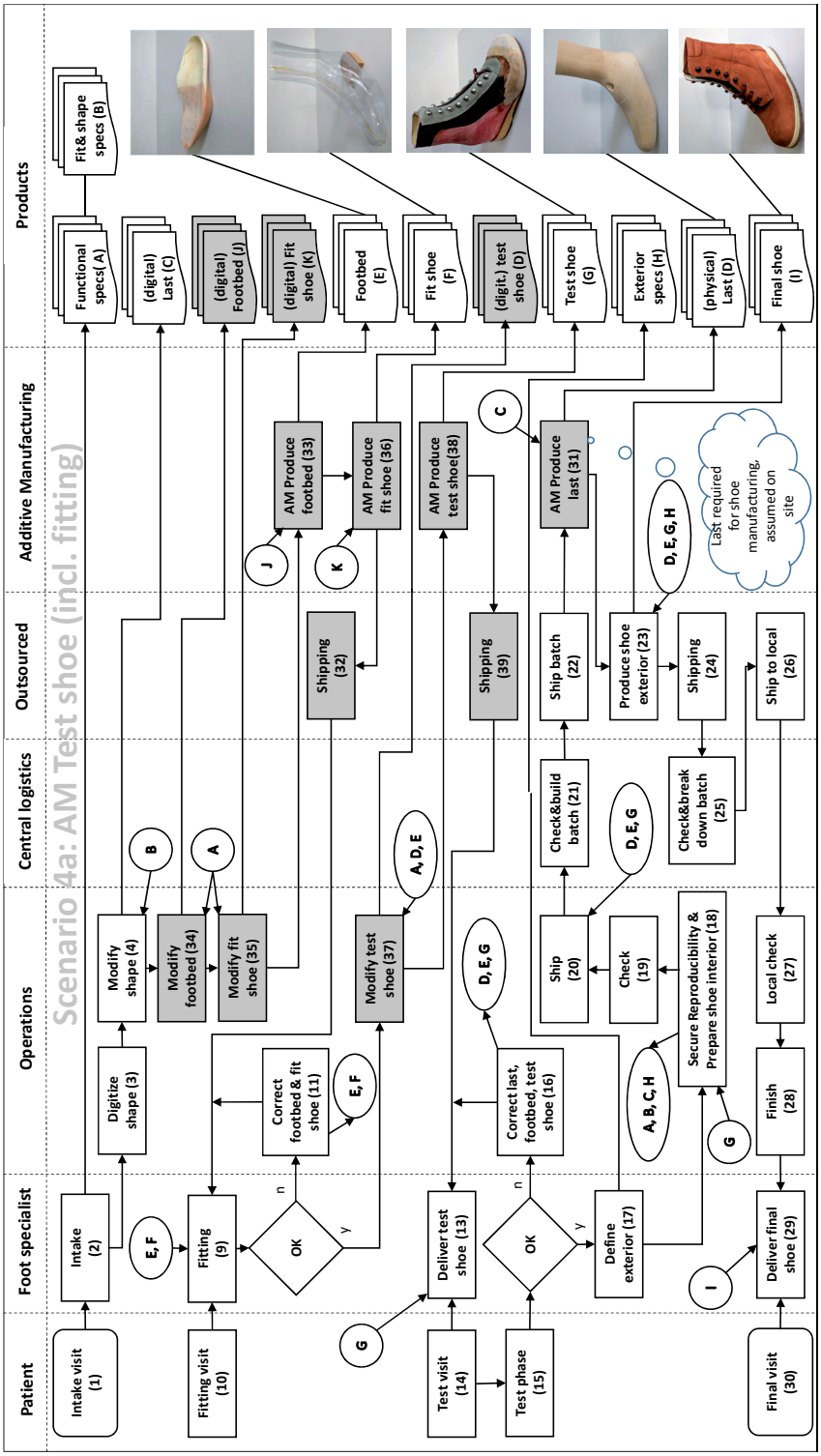


Figure A5.1.5: Process flow Scenario 4a.

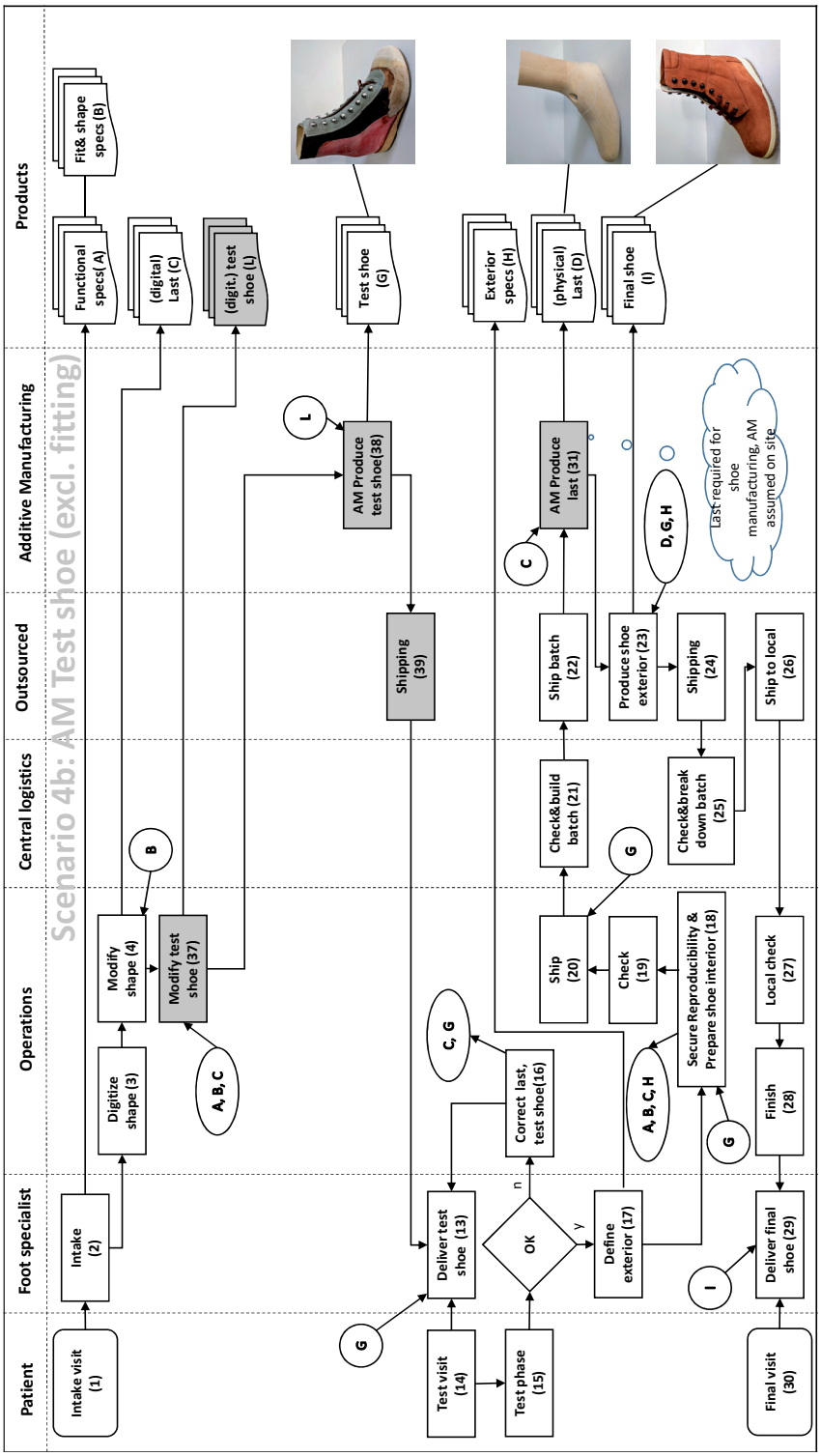


Figure A5.1.6: Process flow Scenario 4b.

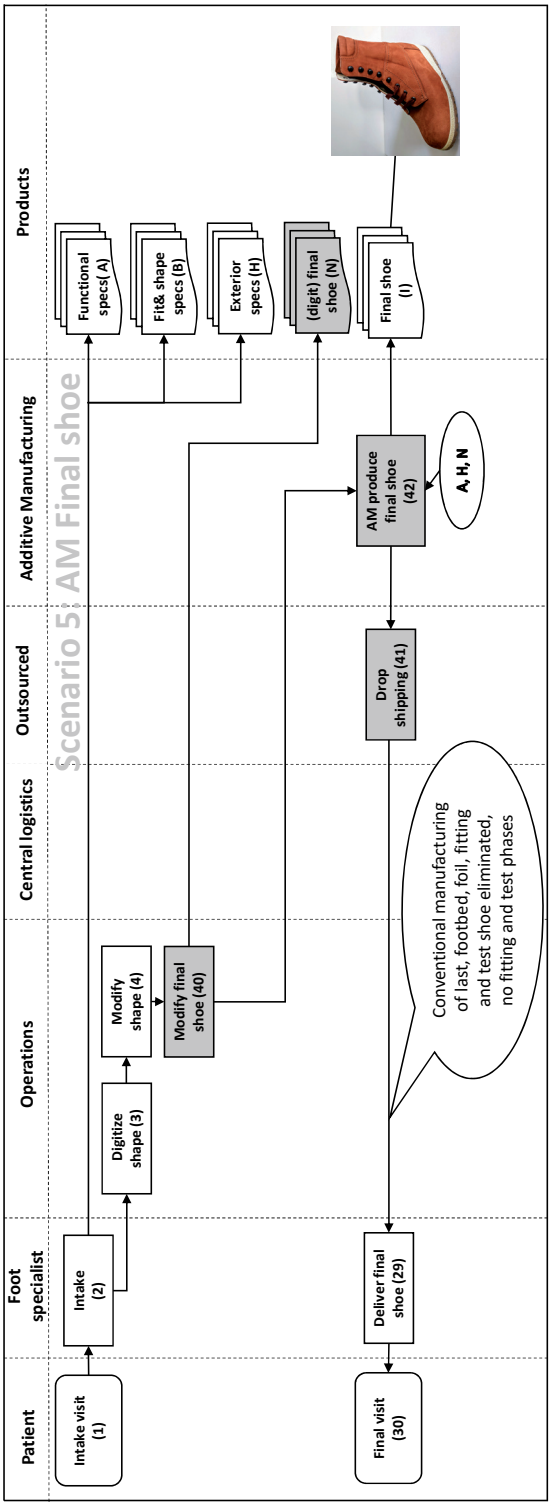


Figure A5.1.7: Process flow Scenario 5.

Appendix 5.2

Table A5.2.1: AM feasibility

Description	Relevant scenarios	Year	AM Technical feasibility score (7-point Likert scale)						
			Definitely possible	Likely possible	Probably possible	Neither possible nor impossible	Probably impossible	Likely impossible	Definitely impossible
AM Production of last	1, 2, 3, 4a, 4b	2020	*						
		2025	*						
		2030	*						
AM Production of foot bed	2, 3, 4a	2020		*					
		2025	*						
		2030	*						
AM Production of fitting shoe	3, 4a	2020		*					
		2025	*						
		2030	*						
AM Production of test shoe	4a, 4b	2020						*	
		2025			*				
		2030	*						
AM Produce final shoe	5	2020							*
		2025				*			
		2030	*						

Table A5.2.2: Cost estimates AM components

Relevant scenarios	Description	2020	2025	2030
1, 2, 3, 4a, 4b	AM Production of last	150.00	90	75
2, 3, 4a	AM Production of foot bed	75.00	55.0	50.0
3, 4a	AM Production of fitting shoe	200.00	150.0	100.0
4a, 4b	AM Production of test shoe		375.0	250.0
5	AM Produces final shoe		750	500

Table A5.2.3: Digital design feasibility, * represents one expert opinion

Description	Relevant scenarios	Year	Digital design feasibility score (7-point Likert scale)						
			Definitely possible	Likely possible	Probably possible	Neither possible nor impossible	Probably impossible	Likely impossible	Definitely impossible
Digital last	1, 2, 3, 4a, 4b	2020		*	*				
		2025	*	*					
		2030	**						
Digital foot bed	2, 3, 4a	2020		*	*				
		2025	**						
		2030	**						
Digital fitting shoe	3, 4a	2020		*	*				
		2025	*	*					
		2030	**						
Digital test shoe	4a, 4b	2020		*	*				
		2025	*	*					
		2030	**						
AM Produces final shoe	5	2020		*	*				
		2025	*	*					
		2030	**						

Appendix 5.3

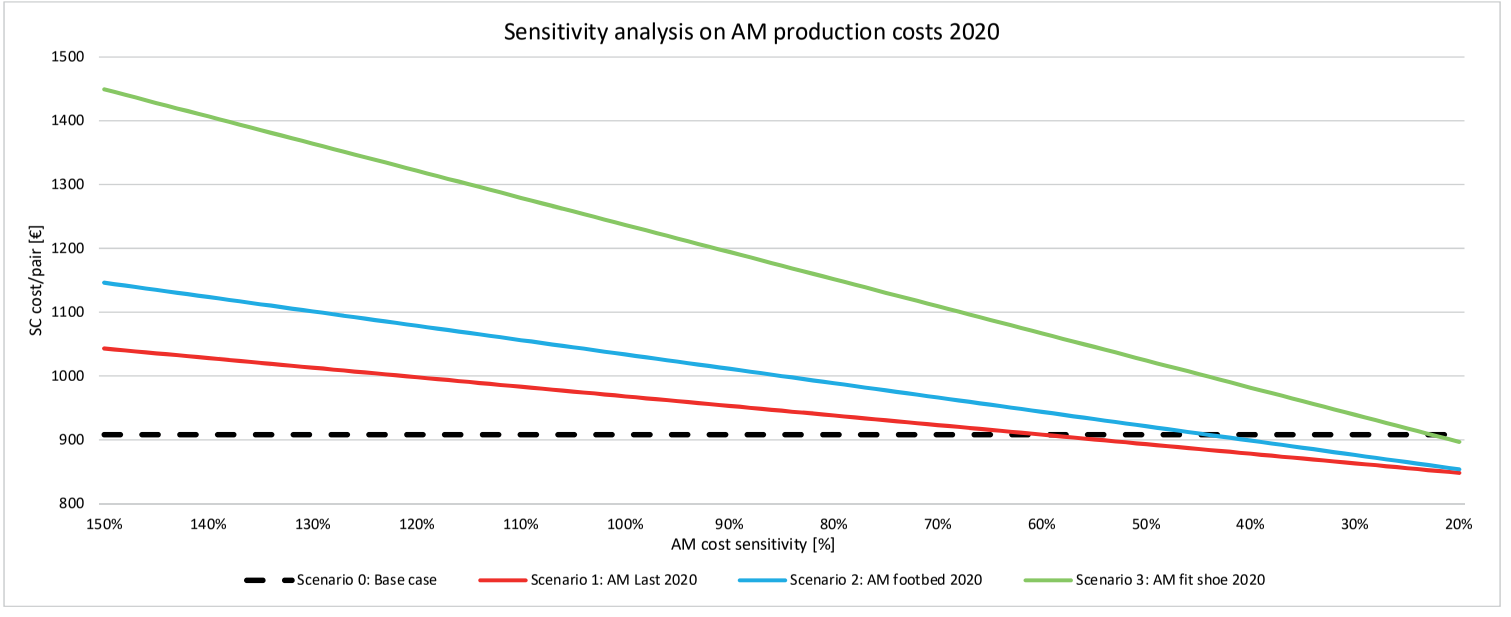


Figure A5.3.1: Effect of AM cost on total SC costs (2020).

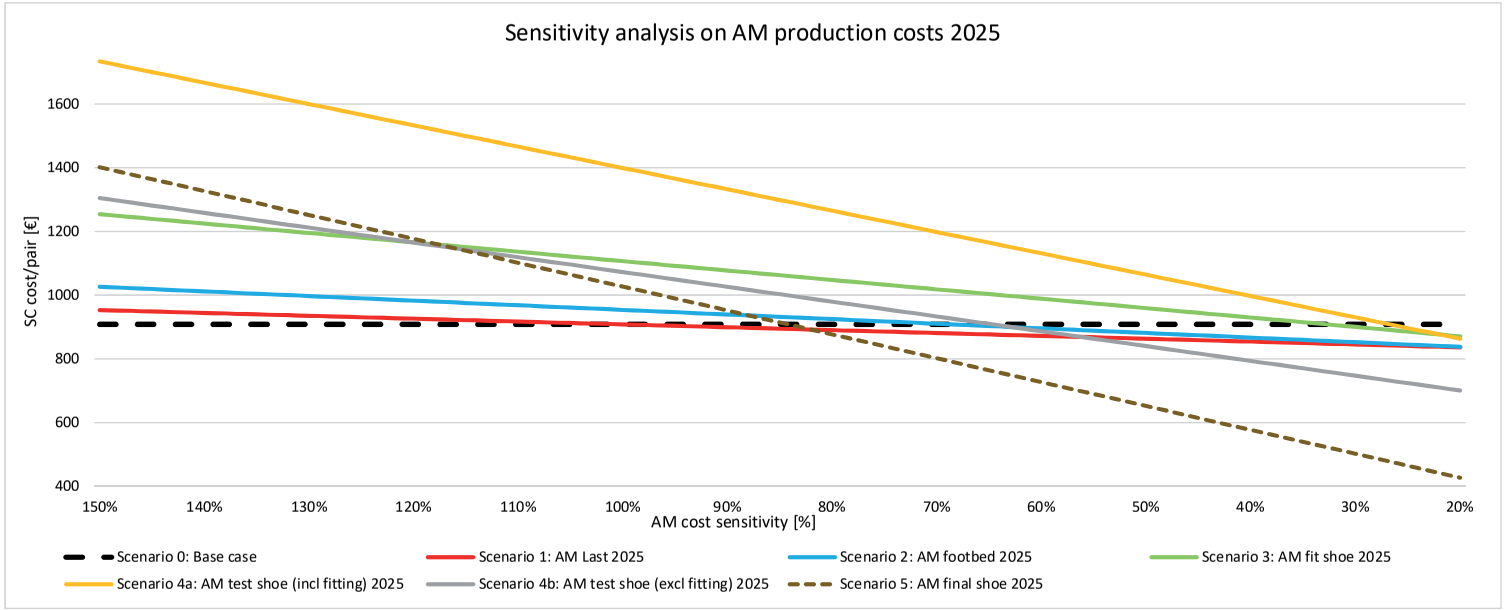


Figure A5.3.2: Effect of AM cost on total SC costs (2025).

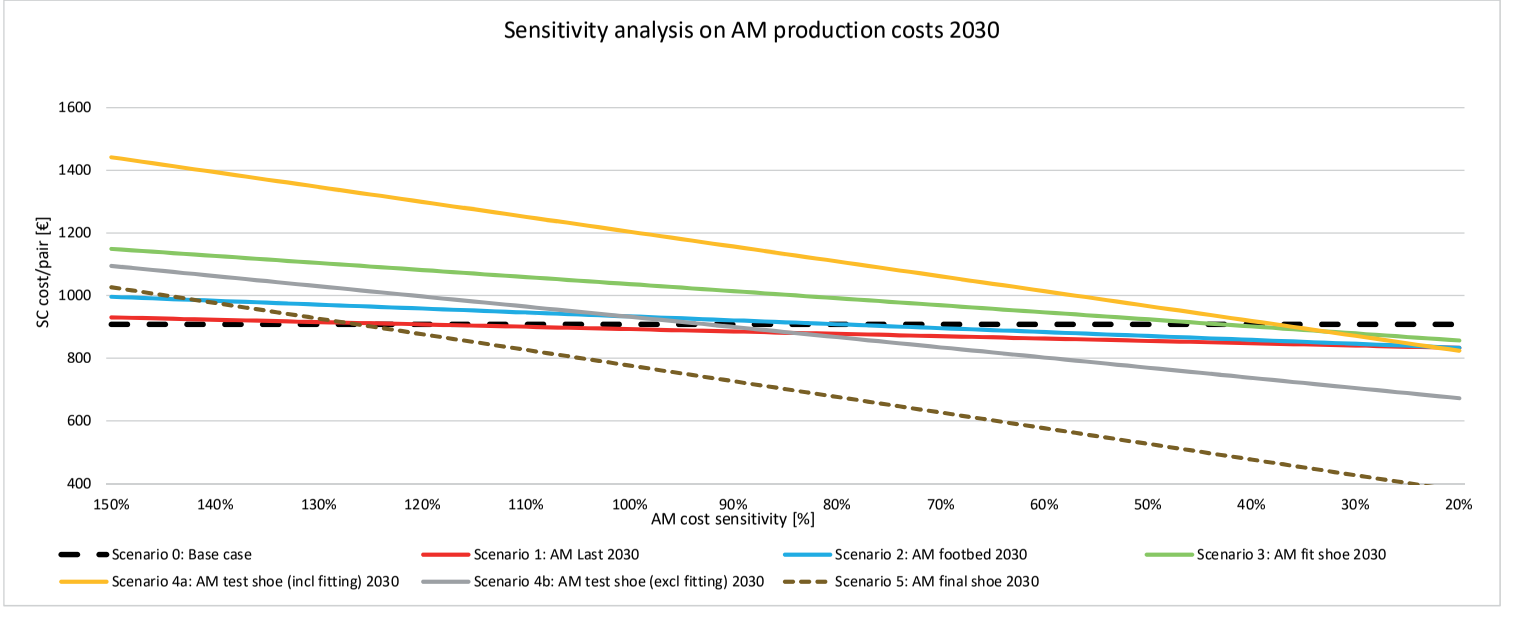


Figure A5.3.3: Effect of AM cost on total SC costs (2030).

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PART 3
BRIDGING THEORY AND PRACTICE

"We cannot solve our problems
with the same thinking we used
when we created them"

Albert Einstein

CHAPTER 6



Conclusions, contribution, implications, and future research

The main objective of this dissertation is to investigate the potential of AM for designing radically improved future SCs. To achieve this main objective, this dissertation includes both empirical as well as theoretical research. While the theoretical research is not context-specific, the empirical research is limited to personalized healthcare products. In line, Chapter 2 builds the theoretical foundation for this dissertation, resulting in a conceptual framework and a research agenda. Thereafter Chapter 3 builds onto this theory by constructing six AM SC mechanisms through literature synthesis. The empirical Chapters 4 and 5 encompass two case studies in personalized medical care supply chains. In one case central AM production of surgical guides replaces distributed AM production and in the other case, AM replaces traditional-manufacturing of orthopedic shoes. Finally, this chapter concludes this dissertation and is structured as follows: Section 6.1 draws the overall conclusions and reflects on the overarching research questions; Section 6.2 articulates the key academic contribution by developing 'CIMO-reasoning chains' thus (partially) confirming the existence of four of the six theoretical mechanisms; Section 6.3 discusses the implications of this research for theory, practice, and methodology; Section 6.4 concludes this dissertation by providing directions for future research.

6.1 Overall conclusions

The main advantages of AM – compared to traditional-manufacturing – include the possibility to manufacture complex shapes, including the possibility to directly integrate functions into the product, and the possibility to manufacture lightweight products. AM is currently considered 'mature' for prototyping and tooling applications, but 'immature' for the manufacturing of final products. Albeit that – for final products – many different applications already exist. These mainly include small, low demand and geometrically complex products, for instance (industrial) spare parts and personalized medical products. AM uses digital designs that easily bypass physical boundaries, and requires no product-specific machines and tools and may therefore allow for in-situ production. This may lead to shorter and simpler SCs. Moreover, customers may be involved in the product design phase. Implementing AM may change the required SC partners, IT systems, facilities, equipment, and people working in the SC. Although SC design theory for AM is limited, relevant progress has been made in this dissertation.

Next, the overarching research questions from Section 1.3 are reflected on.

RQ1. What are the effects of AM on SC cost and lead-time performance?

According to the theory, AM mainly impacts the SC cost, lead-time, assets and sustainability outcomes. Besides 'customization at no extra cost', AM appears to reduce costs, which includes the reduction of cost of raw materials and finished goods inventories, as well as reductions in production, assembly and transportation costs.

However, AM may be more expensive than traditional-manufacturing for larger series and bigger products. Lead-time improvements may also be reached, but mainly for products with complex geometries and for small series.

The empirical research only partly supports these findings: while the lead-time may significantly improve, the costs are higher or, at best, comparable. To be specific, when changing from central to distributed AM, the SC lead-time significantly improves, but the cost significantly increases since investments in assets (machines and facilities) at each of the distributed locations are required. On the other hand, when AM of complete final products replaces traditional-manufacturing of components, lead-time also significantly improves but at competitive SC costs while requirements for buildings, machines, and tools significantly reduce. Note that this is only the case when complete final products are AM-produced. In the case of AM production of tools and components, the SC cost and lead-time performance deteriorate. Also note that these performance changes may be different in other contexts, for instance, in stock-keeping contexts (e.g. military spare parts).

RQ2. Which bottlenecks, serving as thresholds, have to be eliminated before AM can radically improve SC performance?

According to the literature the following thresholds need to be eliminated before AM can become quality-, speed-, and cost-competitive with traditional manufacturing, and eventually radically improve SC performance: product quality needs to be stable and repeatable; product and process certification issues need to be solved; sufficient knowledge about designing for AM needs to be available; also, AM machining technology needs to advance, this includes machines to become faster, cheaper, more automated, and that post-processing issues are solved.

The empirical findings support these theoretical findings. Changing from central to distributed AM is prevented by bottlenecks related to 'advanced AM-machining' and include high AM machine costs, post-processing issues (dust-dispersion), and low manufacturing speed (product cooling related). Solving these bottlenecks will enable distributed AM production and will lead to improved experiential learning through faster feedback, which ultimately leads to improved patient-treatment quality. Changing from traditional-manufacturing to AM is prevented by bottlenecks related to product quality that needs to be stable and repeatable since currently, the quality of AM produced orthopedic shoes is insufficient. Moreover, AM machining needs to advance, since currently, the production costs are too high. Finally, sufficient knowledge about designing for AM is a bottleneck, since traditional craftsmanship needs to be integrated into the digital design. In this case, resolving these thresholds will radically change (disrupt) the existing SC structures.

No evidence has been found that product and process certification issues serve as thresholds.

RQ3. How are AM SC interventions turned into SC performance outcomes, i.e. which mechanisms are induced by AM?

Through literature synthesis, six AM SC mechanisms that, in certain contexts, turn interventions into SC outcomes have been developed. These mechanisms are: 1) co-customization mechanism; 2) in-situ & on-demand mechanism; 3) shared-economies mechanism; 4) digitized stock mechanism; 5) buy-to-fly spin-offs mechanism and 6) functionality-integration mechanism.

To uncover evidence of the existence of the theoretical mechanisms, two empirical studies in personalized medical care SCs have been conducted and evidence for mechanisms 2), 3), 5) and 6) has been confirmed. The rationale behind this will be explained in Section 6.2 and is summarized as follows: changing from central to distributed AM SC configurations, induces mechanisms comparable to the 'in-situ & on-demand mechanism and the opposite of the 'shared-economies mechanism'; Introducing AM in traditional-manufacturing (thus integrating multiple elements into the final product) induces mechanisms comparable to the 'functionality-integration mechanism', and a mechanism that holds elements of the 'buy-to-fly spin-offs mechanism'. The empirical mechanisms are valid for other non-inventory holding contexts, but – if required – can be extended with the inventory holding elements.

No evidence supporting the theoretical mechanisms 1) and 4) has been identified.

6.2 Contribution: CIMO reasoning chains

As introduced in Chapter 1, CIMO-reasoning chains – including mechanisms that turn interventions into performance outcomes within a certain (business) context – can help bridging theory and practice (Holmström et al., 2009). In Chapter 3, six AM SC mechanisms have been synthesized from theory. This section aims to explore to which degree the empirical chapters provide evidence for these six theoretical mechanisms. To identify the (empirical) mechanisms, the results of the empirical chapters 4 and 5 are translated into CIMO-reasoning chains. Thereafter the empirical mechanisms are compared to the six theoretical mechanisms. Evidence for four of the six mechanisms is established. Note that the limited scope of this dissertation (two case studies), made it impossible to find evidence for all six theoretical mechanisms. This section ends with a discussion of the findings.

6.2.1 Centralized versus distributed AM production of surgical guides

The Chapter 4 case investigates the cost and lead-time impact pending a change from centralized AM production of surgical guides to distributed AM production. The literature distinguishes both centralized (Eyers and Potter, 2015, Mellor et al., 2014, Rylands et al., 2016) as well as distributed (in-situ) AM production (De la Torre et al., 2016, Durach et al., 2017, Holmström et al., 2017). Related research investigates the cost performance of distributed AM production of biomedical implants (Emelogu et al., 2016), as well as the lead-time performance of in-situ AM production of coronary stents (Moore et al., 2016), compared to centralized (traditional) manufacturing. Furthermore, Khajavi et al. (2014) investigate centralized versus distributed AM SC configurations, albeit in an industrial spare parts context, whereas our case is in a personalized medical care product context.

In the Chapter 4 case, currently, AM produced (personalized) surgical guides are supplied by an AM service provider to the University Medical Center (UMCs). The UMCs desire improvement of experiential learning through a faster feedback-loop, and therefore wish to turn the digital design into a physical (AM produced) product faster. Since the lead-time of the current outsourced (centralized) AM production is too long, the UMCs consider (faster) in-house (distributed) AM production.

Case study research has been used to map and analyze the current situation, whereas scenario analysis has been used to map and analyze future scenarios. Both the current situation and future scenarios are evaluated on their respective cost and lead-time performances. The results show that distributed scenarios, using the currently available AM technology, reduce the lead-time from 54 to 27 hours due to the elimination of transportation. The costs are however triple. Moreover, the lead-time improvement still does not meet the learning-loop requirements and needs to be further reduced. This may become possible if a solution is found for reducing the product cooling time, which is required to prevent product warping. The high SC costs are caused by expensive machines and necessary facility adjustments to prevent dust-dispersion in each of the distributed locations.

In CIMO-reasoning chain terms, the findings of this research are summarized as follows:

> *When changing from centralized to distributed AM production (I) in the context of surgical guides (C), some SC costs components and SC lead-time reduces (O1a). After all, digital parts distribution replaces physical parts distribution, thus eliminating transportation and making the SC shorter and simpler (M1a). At the same time, some other SC costs components increase (O1b), since investments in machines and adjustments to facilities are required in the multiple (distributed) locations. Moreover, the total order volume is divided over multiple locations, which lowers machine and machine chamber utilization.*

Hence, higher investments have to be amortized over the smaller series (M1b). Note that expensive AM machines and measures to prevent dust dispersion and product warping are bottlenecks serving as thresholds, and overall prevent this mechanism from becoming effective.

Figure 6.1 visualizes the result of this study.

This reasoning chain distinguishes two mechanisms; M1a and M1b. Mechanism M1a matches with the 'in-situ & on-demand mechanism' developed through literature synthesis and explained in Figure 3.3 in Section 3.4.2.2. Note that the intervention of the theoretical and the empirical mechanism differ: The intervention in the theoretical mechanism relates to a change from traditional-manufacturing to AM, while the intervention in the empirical mechanism relates to a change from central AM to distributed AM. Even though the interventions differ, both the theoretical as well as the empirical mechanism point at a reduction of transportation requirements which reduces the lead-time and the amount of SC steps which corresponds with the disintermediation concept (Mills and Camek, 2004). Also, note that, although in the distributed AM scenarios the CODP continues to be EtO, effectively the CODP moves downstream, closer to the point of use.

Mechanism M1b matches with the 'shared-economies mechanism' synthesized from theory and explained in Figure 3.4 in Section 3.4.2.3. Note first of all that the intervention of the theoretical and the empirical mechanism are reversed: the theoretical intervention is to centralize AM production, whereas the empirical intervention is to distribute AM production. Hence, the mechanisms also act in reverse. Mechanism M1b shows that – although AM does not require amortization of expensive product-specific tools (Berman, 2012, Holmström et al., 2016, Thiesse et al., 2015) and propagates 'economies-of-one' (Fawcett and Waller, 2014, Holmström et al., 2010) – the decision to switch from centralized AM to distributed AM causes cost to increase, due to high investments in (distributed) equipment and lower (distributed) order volumes. To put it simply: mechanism M1b represents the opposite of the economies-of-scale concept. Rather unexpected, and new compared to the theoretical mechanism, is the multiplying cost effect of distributed AM production due to both investments in distributed machines and facilities, as well as the worsening of machine and machine chamber utilization due to the order volume being spread over the distributed locations.

Finally, note that the mechanisms M1a and M1b possess opposite cost curves. Therefore, future SC designs will need to trade off these two mechanisms to reach positive SC cost performance. Moreover, if in the current (centralized production) situation, transportation cost are high – for instance in cases of long distances or due to difficult-to-reach locations – the cost benefits when implementing distributed production (through of mechanisms M1a) will increase and may easier outweigh the cost disadvantages of mechanism M1b.

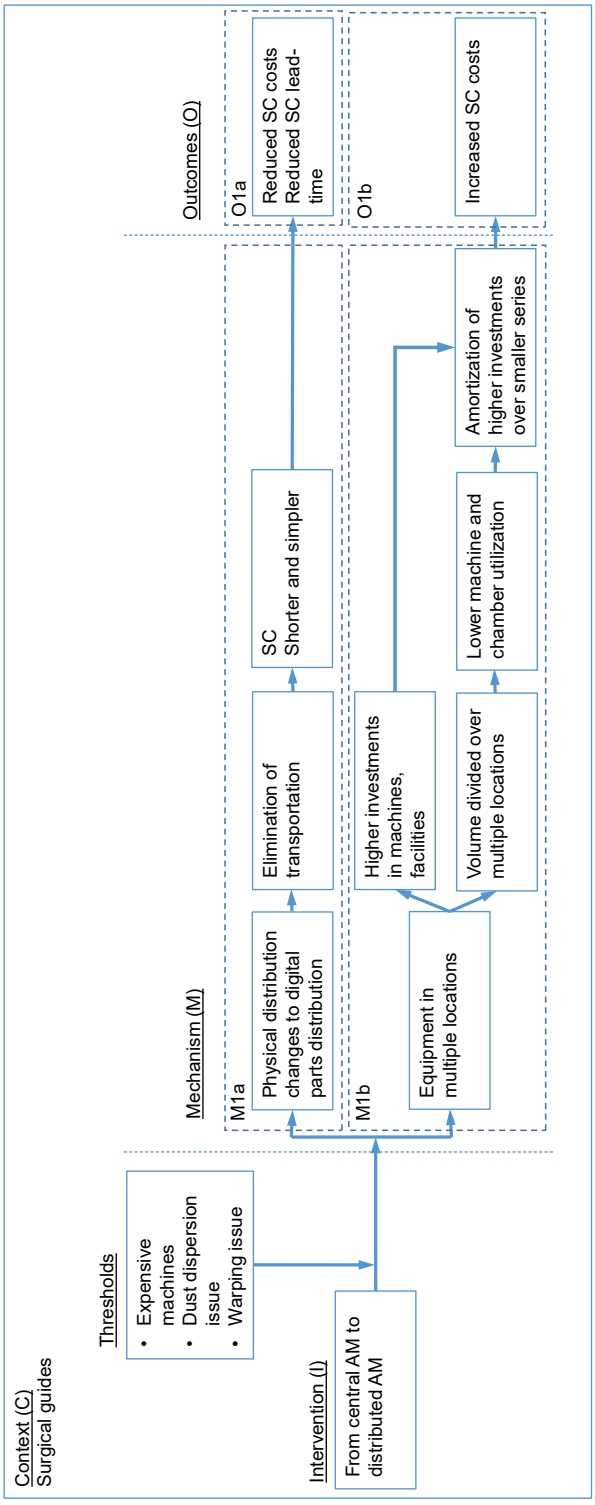


Figure 6.1: CIMO-reasoning chains central vs distributed surgical guides case.

To wrap up this section: the combination of M1a and M1b is intertwined with the central vs distributed intervention, and the empirical mechanism M1a provides evidence of the existence of the theoretical 'in-situ & on-demand mechanism'. Moreover, empirical mechanism M1b provides evidence of the existence of the opposite of theoretical 'shared-economies mechanism', since the intervention, mechanism, and outcomes are all reversed.

6.2.2 Implementing AM in traditional orthopedic shoe manufacturing

Chapter 5 presents a case study where AM is introduced in traditional orthopedic shoe manufacturing. The literature study reveals no examples of AM produced orthopedic shoes, whereas in the fashion industry examples of complete AM produced shoes are encountered, yet the quality is considered poor (Kim et al., 2019, Vanderploeg et al., 2017). Moreover, applications of AM for fashion shoes include the production of molds (Chung et al., 2003), lasts (Amza et al., 2019), and for shoe personalization (Meier et al., 2019). Although AM production of complete orthopedic shoes is not (yet) possible, examples of applications for orthopedic shoe elements exist, for instance for production of insoles (Salles and Gyi, 2013a, Salles and Gyi, 2013b) or orthotics (Jordan, 2019). Earlier SC research, where AM replaces traditional-manufacturing for personalized medical products, has been done by Emelogu et al. (2016) into SC cost effects for biomedical implants, and by Moore et al. (2016) into the SC lead-time effects for coronary stents.

The Chapter 5 case company operates in a challenging environment where – due to rapidly rising healthcare costs in the Netherlands – health insurers annually reduce the reimbursements they pay for the patient-treatments. So far, the shoe manufacturer has been able to compensate for this income loss by applying lean techniques, for instance by process standardization and partial outsourcing. However, cost-savings through these incremental process improvements will reach an end at some point, and AM is considered a promising solution.

Case study research and scenario analysis have been used to analyze the effects of introducing AM. The current – traditional-manufacturing – processes have been mapped and cost, volume, and lead-time data have been gathered. Thereafter, future scenarios have been simulated, where AM replaces traditional-manufacturing for tools, shoe components and eventually for complete shoes. The current situation and future scenarios have been evaluated on their respective SC cost and SC lead-time performance.

The findings show that, with the current state of technology, AM production of complete orthopedic shoes is technically infeasible, only AM production of tools (e.g. lasts) and components (e.g. footbeds) is possible. However, replacing traditional-manufacturing of tools and components by AM production leads to higher SC costs and worsens SC

lead-time. The findings also show that once AM of complete orthopedic shoes becomes possible – which is expected to happen in 5-10 years – AM SCs very likely become cost-competitive with traditional manufacturing and SC lead-time reduces by up to 90% due to the elimination of 70% of the SC steps. Also, positive effects on raw material usage and environmental footprints can be achieved. With the introduction of AM for complete orthopedic shoes, the existing relations within the current SC actors will be disrupted. For instance, fewer and other types of suppliers are required, and peoples' jobs, facilities, machines, and tools requirements change completely. However, bottlenecks currently serve as thresholds and have to be overcome before this can happen. First of all, AM production of complete orthopedic has to be possible. Second, AM production prices have to drop below €630/pair (today's value), and third, traditional craftsmanship has to be transferred into a 'perfect', hence reliable, digital design.

In CIMO-reasoning chain terms the findings of this research are summarized as follows:

> *Introducing AM production for complete orthopedic shoes (I) in traditional orthopedic shoe manufacturing (C), reduces most SC costs and SC lead-time (O2a). After all, physical storage and distribution changes to digital storage and distribution, thus reducing material handling and transportation requirements. Also, one machine is used for different types of products, which reduces the requirements for buildings, equipment, and suppliers, making SCs shorter and simpler (M2a). Moreover, the need for raw material, the emissions, and the footprints reduce (O2b) due to the additive nature of AM (M2b). However, bottlenecks serving as thresholds currently exist and prevent this mechanism from becoming effective. AM production of complete orthopedic shoes has to become possible since this mechanism is not effective for orthopedic shoe tools or components. Moreover, AM production costs have to reduce, and traditional craftsmanship has to be translated into a high-quality digital design.*

Figure 6.2 visualizes the result of this study in CIMO-terms.

The empirical reasoning chain of this research comprises two mechanisms: M2a and M2b. Mechanism M2a is related to the 'functionality integration mechanism' synthesized from literature and explained in Figure 3.7 in Section 3.4.2.6. Both the empirical and the theoretical mechanisms explain that introducing AM allows for integration, and hence reduction, of production steps into one final product, which is in line with SC disintermediation. This leads to shorter SC lead-time and potentially to reduced SC costs. Moreover, in both the empirical and theoretical studies, the availability of AM design knowledge is considered important, where the empirical study provides more detail by stating that traditional craftsmanship needs to be integrated into the high-quality design.

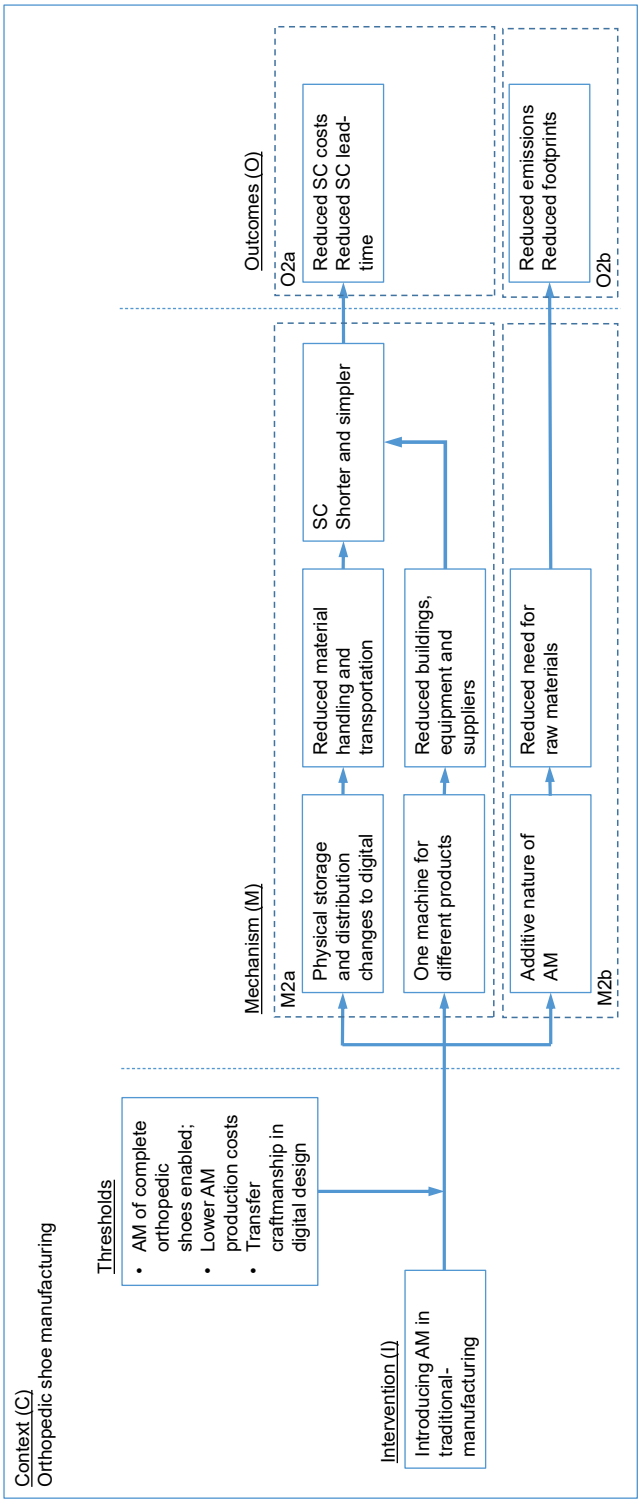


Figure 6.2: CIMO-reasoning chains AM in traditional orthopedic shoe manufacturing.

Considering similarities in sustainability-related SC outcomes, empirical mechanism M2b has some resemblance with the 'buy-to-fly spin-offs mechanism' explained in Figure 3.6 in Section 3.4.2.5, albeit that the empirical mechanism does not cover the essence – the spin-offs during use – of the theoretical mechanism.

To wrap up this section: the combination of M2a and M2b is intertwined with the switch from traditional-manufacturing of components to additive manufacturing of the complete product. The empirical mechanism M2b provides evidence of the existence of the 'functionality-integration' mechanism, while empirical mechanism M2b has some resemblance to the 'buy-to-fly spin-offs mechanism'.

6.2.3 Discussion

This section discusses the empirical and theoretical mechanisms on a meta-level as well as the transferability of the mechanisms to other contexts.

Both case studies have been executed in patient-specific healthcare contexts and (partial) evidence of the existence of four empirical mechanisms has been found. Table 6.1 summarizes the findings.

Table 6.1: Empirical versus theoretical AM SC mechanisms

Intervention	Empirical mechanism	Related theoretical mechanism	SC performance outcomes
From centralized AM to distributed AM	M1a	'in-situ & on-demand mechanism'	Reduced costs Reduced lead-time
	M1b	'shared-economies mechanism' (reversed)	Increased costs
From traditional-manufacturing of components to AM of the complete final product	M2a	'functionality-integration mechanism'	Reduced costs Reduced lead-time
	M2b	'buy-to-fly spin-offs mechanism' (partly)	Reduced emissions Reduced footprints

When examining the reasoning chains in Figures 6.1 and 6.2 on meta-level, overlapping mechanism elements as well as overlapping thresholds are observed. An overlapping mechanism element is 'digital distribution' in M1a and M2a, leading to shorter and simpler supply chains. Hence, the most relevant traditional concept appears to be SC disintermediation (Mills and Camek, 2004). Note that the disintermediating effect – the number of reduced steps – is stronger when AM of the complete final product replaces traditional-manufacturing of components than when distributed AM replaces centralized AM. Besides, digital distribution is not unique to AM supply chains but may be applicable in any context where digital designs are used. For instance, digital designs may be used in combination with subtractive (traditional) techniques, e.g. CNC milling.

The overlapping bottlenecks, serving as thresholds in both case studies, include high AM (production/machine) cost and immaturity of AM (stable, repeatable, high-quality products), which is in line with the findings from theory in the Chapters 2 and 3.

As discussed in Section 3.5, mechanisms are considered separately in theory, but in practice combinations of mechanisms exist (Hsuan Mikkola and Skjøtt-Larsen, 2004). This is in line with the empirical findings: although the mechanisms M1a, M1b, M2a, and M2b can be considered individually to understand how interventions are turned into outcomes, the mechanisms M1a and M1b (or M2a and M2b) should not be considered separately to determine the overall impact of interventions on outcomes. An example is the opposite effect on SC cost of M1a and M1b.

In the cases, two interventions have been investigated: (1) AM of the complete final product replaces traditional-manufacturing of components, and (2) distributed AM replaces central AM. However, with maturing AM, combinations of both interventions will likely be more in line with business reality. To illustrate, Moore et al. (2016) provide a test case where coronary stents, that are currently traditionally (mass) manufactured is changed to AM production (first intervention), thus allowing for distributed (AM) manufacturing (second intervention) in the operating room. In line, Emelogu et al. (2016) have investigated in-situ AM production (first intervention) of biomedical implants replacing traditional central manufacturing (second intervention). To further complicate this: introducing AM may at the same time allow a change from non-customized products (MtS) to personalized products (MtO/EtO) (third intervention), and may also allow involving customers in the design process (fourth intervention). In other words: to fully exploit the SC advantages that AM offers, multiple interventions should be considered. To study the effects of these combined interventions will require combining the empirical mechanisms M1a, M1b, M2a and M2b in one CIMO-reasoning chain. Moreover, the related CIMO-reasoning chain will require extension with inventory-related, as well as customer involvement-related elements, which will likely be in line with the 'digitized stock mechanism' and the 'co-customization mechanism' as discussed in the Sections 3.4.2.4 and 3.4.2.1. Accordingly, Figure 6.3 is developed to support the decision-making process when designing SCs that fully exploit the advantages of AM. This figure mentions the intervention choices, as well as the related AM SC-mechanisms.

One of the purposes of creating CIMO-reasoning chains is to identify mechanisms that can be transferred (generalized) to other contexts. In line, the empirical mechanisms M1a, M1b, M2a, and M2b are likely transferable to other (comparable) contexts. For example, when a central AM to distributed AM intervention is considered, the combination of mechanisms M1a and M1b may well be used to design SCs in other, non-inventory keeping or patient-specific contexts. As mentioned in Section 6.1.1, with increasing distances or when locations are difficult-to-reach (e.g. war zones or polar areas) (De la Torre et al., 2016), the cost and lead-time benefits may well increase.

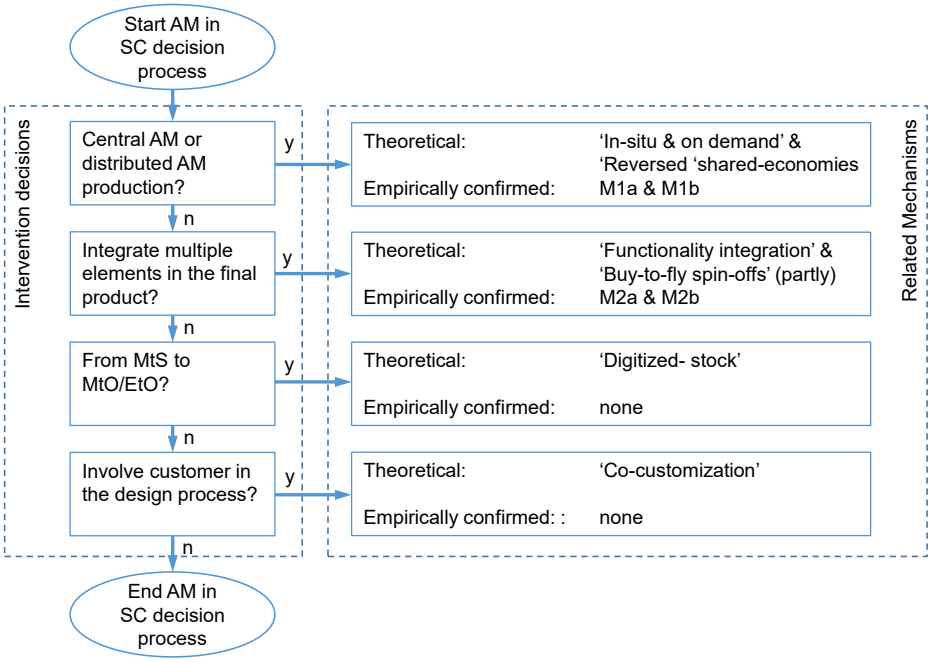


Figure 6.3: SC intervention choices enabled by AM and related AM SC mechanisms.

With regards to the transferability of the mechanisms M2a and M2b, note that the empirical mechanism refers to a personalized medical products SC, whereas the theoretical mechanism refers to construction and assembly manufacturing contexts. In the construction industry thermodynamic functions – for instance, cooling channels – may be integrated in the design of the final product (Kothman and Faber, 2016), whereas in assembly manufacturing mechanical functions – for instance, products with assembled parts inside – may be integrated in the product design (Atzeni and Salmi, 2012, Wagner and Walton, 2016, Yang and Zhao, 2015). In line, with the orthopedic shoe case, also mechanical functions are integrated into the design of the final orthopedic shoe. This implies that empirical mechanism M2a and M2b may well be used to design SCs in, for instance, the construction or assembly manufacturing industry. Nevertheless, personalized medical products SCs are non-inventory holding. Therefore adding the inventory-keeping elements to the mechanisms for other contexts may be needed.

No evidence has been found supporting the theoretical 'co-customization mechanism' (Section 3.4.2.1) and the 'digitized stock mechanism' (Section 3.4.2.4). This is logical since the 'co-customization mechanism' requires customer involvement in the design phase and this was not in the scope of the empirical studies. Moreover, the 'digitized stock mechanism' requires intervention from keeping inventory to a new situation where no

inventory is kept. This requires the CODP changes from MtS to MtO or EtO. This was also not in the scope of the empirical studies.

To wrap up this section: evidence of existence for three out of the six mechanisms synthesized from the theory has been found in the empirical studies (M1a, M1b, and M2a), and partial evidence of existence has been found supporting a fourth mechanism (M2b). Moreover, as will be outlined in Section 6.4, future research can discover evidence for the remaining two theoretical mechanisms as well as additional evidence for the already (partially) proven mechanisms. Moreover, to fully exploit the advantages of AM, combinations of interventions are necessary. This will require an analysis of combined AM SC mechanisms.

6.3 Implications for theory, practice, and methodology

In each of the individual Chapters 2 to 5, the implications for theory and practice have been explained. Additionally, this section explains the overall theoretical, practical and methodological implications of this dissertation.

The main theoretical implication of this dissertation is the development of six and (partial) confirmation of the existence of four AM SC mechanisms, which can be used to design a significantly improved supply chain using AM. These mechanisms increase the understanding of how AM related interventions can be turned into SC outcomes. Note that the mechanisms depend on the chosen intervention and that in this dissertation – in a personalized medical products SC – two interventions were explored: central AM to distributed AM and traditional-manufacturing of components to AM of the complete final product. The working of these mechanisms can, under conditions, be transferred to other contexts, and, if required, combined or extended with other mechanisms.

The implications for the practice of the individual cases are discussed in Sections 4.5 and 5.6. The overarching implication for practice is that currently, implementing AM, at best causes incremental SC performance improvement, although the case studies show that SC performance can even worsen. Bottlenecks, serving as thresholds currently prevent the effective roll-out AM. However, technology develops fast and these bottlenecks will be eliminated. At that moment distributed (in-situ) AM may become cost-effective as will be switching from traditional-manufacturing to AM. When this happens (not 'if' this happens), existing SCs will be disrupted and only those companies that are prepared will survive. Furthermore, the orthopedic shoe case is exemplary by showing that AM by itself is not the holy grail and smart combinations of digital techniques are required, a concept that Mandolla et al. (2019) call 'digital twin'. An important learning from the orthopedic shoe case is that having an excellent digital design is key, although this sounds easier than it actually is. Traditional craftsmanship needs to be digitized, which

requires other digital techniques, for instance, data analytics and big data. Therefore, well before AM reaches maturity, business managers need to invest in the digitization of the SC in order to be future-proof. For instance, by having a perfect digital design ready when AM reaches maturity.

Finally about the implications for methodology. Case study research combined with scenario analysis has proven to be useful. Moreover, DSR's CIMO-logic has demonstrated to be helpful to create transferable knowledge about the mechanisms. Note that, in this dissertation, scenario analysis was used to predict the effects of innovative technology (AM) on the (future) design of SCs. Hence, the CIMO-logic was used to predict reasoning chains before occurrence. Additionally, throughout this dissertation bottlenecks (serving as 'thresholds' that have to be eliminated before mechanisms can become effective) were identified. These thresholds show resemblance with the 'restraining forces' (as opposed to the 'driving forces') of the force-field analyses of the famous Lewin (1943) change model. Inherent to innovative technologies is that there will always be restraining forces (thresholds) preventing the newly induced mechanisms from becoming effective. Therefore, to predict the effects of innovative technologies, it is suggested to add the thresholds (T) preventing mechanisms from becoming effective to the CIMO-logic. The adapted definition of the CI(T)MO-reasoning chains would become (see also Figure 6.4):

> *"In contexts where the prediction of innovative technologies into an unknown future is required (C), the technological change (I) produces mechanisms (M) which are turned into outcomes (O), provided that thresholds (T) are eliminated."*

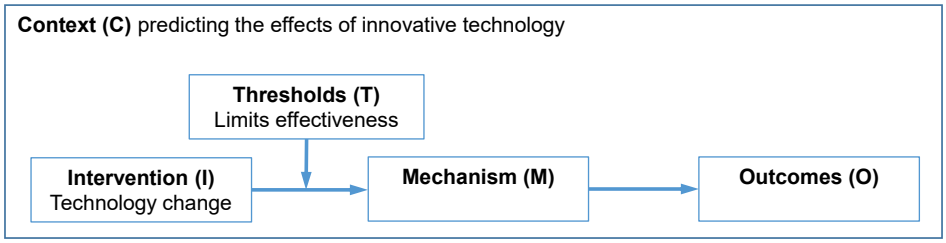


Figure 6.4: Adapted CIMO-logic to CITMO-logic.

6.4 Directions for future research

As pointed out by Swab (2017), society is on the verge of the 4th industrial revolution, where combinations of innovative technologies will drastically change the world we live in. For that reason, future research should continue studying how innovative technologies can significantly improve supply chain performance. Following the

research agenda derived from theory in Chapter 2, this section concludes this dissertation by providing directions for future research in the retrospective of the complete dissertation. Note that the related research questions are listed in Table 6.2.

With the elimination of bottlenecks serving as thresholds AM for final products will develop towards maturity, thus allowing the full exploitation of the benefits of AM. To be prepared, continued research is recommended about how SCs should be redesigned while AM develops towards maturity. Also, combinations of AM with other technologies (digital twins) – for instance, blockchain, data analytics, or combinations of (not yet existing) technologies – is an asset.

Furthermore, healthcare costs are high and rising (OECD/EU, 2018, RIVM, 2018). Consequently, the pressure for the healthcare provider to cut costs increases, while at the same time also the expected (service) quality levels rise. In line with this dissertation, it is recommended to continue future research in this healthcare context. Additionally, due to an aging and shrinking population, the Limburg region is economically lagging compared to other regions in the Netherlands. Therefore, future research should preferably also add value to the local (Limburg) region where several large medical devices companies hold their central European headquarters and distribution centers, for instance, Medtronic, Boston Scientific, and Abbott Technologies. Collaboration with these companies would be ideal.

Note that, although this research focused on medical care products, other contexts are most certainly also interesting. Considering the high investments in inventories, the spare parts industry can vastly benefit from AM (Chekurov and Salmi, 2017, Knofius et al., 2016, Liu et al., 2014, Meisel et al., 2016). In this area co-operation with other researchers is an option and cooperation with Aalto University in Finland is already ongoing.

As mentioned in Chapter 1, academic knowledge about the effects of AM on SCs is limited and that is where this dissertation adds value through developing and validating AM SC mechanisms. Still, it is relevant to continue investigating existing and new mechanisms to create transferable knowledge. Future research can either provide more evidence for the four empirical mechanisms, or find evidence for the remaining two theoretical mechanisms, or discover evidence for new – undiscovered – mechanisms.

Moreover, combining interventions will likely trigger combinations of mechanisms as indicated in Section 6.1.3. Note that in the healthcare context, many providers exist with central, traditional-manufacturing, including inventory keeping (MtS). For example, the earlier mentioned Medtronic, Boston Scientific and Abbott Technologies in the Limburg region. If those companies desire to fully exploit the benefits of AM, they may consider switching to distributed AM, without inventory keeping (MtO/EtO).

Finally, considering the increased attention for the environment, or in SCM terms: to better balance the triple bottom line by designing sustainable SCs (Bals and Tate, 2018), more attention for the sustainability effects (for instance raw material usage and footprints) of applying AM in the SC is recommended. Moreover, this dissertation primarily evaluated cases on the outcomes 'costs' and 'lead-time', which proved to be valuable. However, as explained in Section 1.1, supply chains produce a mix of outcomes (cost, responsiveness, assets, reliability, flexibility, resilience, security, sustainability, innovation). Therefore future research can be evaluated on more outcomes than just cost and lead-time.

Table 6.2: Future research questions

Related to maturing technology
• How can SCs – preferably in a Limburg healthcare context – be redesigned to fully exploit the advantages of AM, while AM develops towards maturity?
• How can AM be combined with other digital technologies to design significantly improved SCs?
Related to AM SC mechanisms
• How do the empirically confirmed mechanisms behave in other contexts?
• What mechanism does 'involving customers in the design process' trigger in an AM SC, and how is this in line with the 'co-customization mechanism'?
• What mechanism does changing the CODP from MtS to MtO/EtO trigger in an AM SC, and how is this in line with the digitized stock mechanism?
• What other mechanisms, besides the ones in this dissertation, exist and how do they function?
• What mechanisms do combinations of various interventions trigger, and to what outcomes do they lead?
Related to SC performance outcomes
• How can AM – besides cost and lead-time – help to improve the SC outcomes assets, reliability, flexibility, resilience, security, sustainability, and innovation?

Although this dissertation contributes to the AM SC knowledge base, the knowledge gap about the future effects of innovative technologies on supply chains continues to be significant, and will probably increase with increasing digitization. For a single researcher, it is impossible to grasp the complexity of this very rapidly digitizing world. Therefore, future research should be executed in collaboration with other research institutions, governments, and businesses (the so-called 'triple helix'). Co-operation with the recently established 'Brighlands Institute for Supply Chain Innovation (BISCI)', partnering with Maastricht University, the Province of Limburg, TNO, and Fontys University of Applied Science, can be a good vehicle to achieve this cooperation. In fact, a partnership has already been set-up.

To wrap up this dissertation: both from a theoretical as well as an empirical perspective AM offers great opportunities for designing significantly improved supply chains which are shorter and simpler. However, although the lead-time significantly improves, in-situ manufacturing is prevented by high AM production costs and technological AM issues. Besides, merely using AM to replace elements of the traditional SC can deteriorate SC performance. Therefore, AM's shape freedom advantage – including the possibility to integrate functions into the final product – needs to be fully exploited. A complete redesign of the existing supply chain is required. The mechanisms, developed in this dissertation, may serve as a tool for SC (re)design. A redesigned SC, where AM is accurately applied, may significantly improve SC performance, and may radically change existing SC structures (SC disruption). Yet, AM technology has to advance, AM costs have to drop and traditional craftsmanship needs to be inserted into the digital design.

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Supply Chain Disruption

The Game-changing Impact of Additive Manufacturing

Additive Manufacturing (AM) – also known as 3D-printing – is one of the digital technologies associated with the 4th industrial revolution. The objective of this dissertation is to investigate the potential of AM for designing vastly improved future supply chains.



Victor Verboeket

The main body of this dissertation consists of four academic articles and the key scientific contribution is the bridging of theory and practice through the development and empirical confirmation of four 'mechanisms', which can be used to design significantly better-performing supply chains.
The results show that AM offers great opportunities for designing significantly improved supply chains, but bottlenecks, serving as thresholds prevent the full roll-out of AM. Besides, merely using AM to replace elements of the traditional supply chain can deteriorate performance. Therefore, to fully exploit AM's specific advantages, a complete redesign of the existing supply chain is required. The mechanisms developed in this dissertation may serve as a tool for supply chain (re)design. Applying AM may ultimately lead to a radical change – disruption – of the existing supply chain structures.

Victor Verboeket (1968) aims at bridging the academic and the business world. He studied mechanical engineering and business. After an almost 20 years career in various supply chain management positions in international companies, he switched to higher education in 2012. Since 2020, his scientific, teaching and business activities are integrated into a new role at the Brightlands Institute for Supply Chain Innovation (BISCI) of Maastricht University.

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