# The Impact of Additive Manufacturing on Supply Chains and Business Models:

## Qualitative Analyses of Supply Chain Design, Governance Structure, and Business Model Change

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## Vorwort

Diese Dissertation markiert das Ende eines langen und arbeitsreichen Prozesses. Sie ist im Rahmen meiner Tätigkeit als wissenschaftliche Mitarbeiterin am Fachgebiet Unternehmensführung und Logistik an der Technischen Universität Darmstadt entstanden. Auf diesem Weg habe ich viel Unterstützung erfahren, wofür ich mich gerne herzlich bedanken möchte.

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Darmstadt, im Juni 2022 — Anne Friedrich

## Zusammenfassung

Jüngste Krisen wie die COVID-19 Pandemie stellen globale Lieferketten bzw. Supply Chains vor Herausforderungen. Der disaggregierte, „feingliedrige“ Charakter solcher traditionellen Supply Chains birgt ein hohes Störungsrisiko. Aktuelle Beispiele wie anhaltende Lieferengpässe (z. B. der Chipmangel in der Automobilindustrie) zeigen, dass häufig keine schnellen Lösungen Abhilfe schaffen können. Dies setzt Unternehmen zunehmend unter Druck, das Design ihrer globalen Lieferketten zu überdenken und Maßnahmen zur Erhöhung der Widerstandsfähigkeit zu ergreifen. Der additiven Fertigung (AF) wird das Potenzial zugesprochen, einen Wandel von globalen zu kürzeren, dezentralisierten und damit widerstandsfähigeren Supply Chains zu ermöglichen. Das Alleinstellungsmerkmal der AF liegt in der inhärent digitalen und flexiblen Natur der Technologien. Ihre spezifischen Eigenschaften stellen eine ortsunabhängige Fertigung nahe oder sogar am Ort des Verbrauchs in Aussicht, bei der die Fertigungsinfrastruktur universell nutzbar wird und daher flexibles Outsourcing an lokale Partner ermöglicht. Darüber hinaus wird erwartet, dass die Charakteristiken der AF traditionelle Geschäftsmodelle infrage stellen.

Die Motivation für diese Dissertation liegt in den skizzierten Potenzialen der AF und den erwarteten Auswirkungen auf die Gestaltung von Lieferketten und Geschäftsmodellen begründet. Die bestehende Forschung weckt hierzu hohe Erwartungen, jedoch mangelt es bisher an konkreten Erkenntnissen aus spezifischen Anwendungsbereichen. Die vorliegende Dissertation leistet einen Beitrag zur Schließung der Lücke zwischen literaturbasierten Visionen und derzeit entstehenden realen Geschäftsmodellen und Lieferkettendesigns bzw. Supply Chain Designs für die AF. Dabei wird die AF als ein potenzieller Eingriff („*intervention*“) aus der Unternehmensumwelt verstanden, welcher eine Anpassung von Geschäftsmodellen und Supply Chain Strukturen erfordert, um eine Passfähigkeit („*fit*“) aufrechtzuerhalten. Ziel dieser Dissertation ist es, ein tiefes Verständnis für diese Anpassungsmechanismen und damit für die inneren Kausalzusammenhänge zu entwickeln, welche die Wahl des Supply Chain Designs und die Geschäftsmodellentwicklung für die AF beeinflussen. Die Konzentration auf die Beweggründe („*rationales*“) und die zugrunde liegenden Verhaltensmuster wird in dieser Dissertation primär in explorativen (*wie* und *warum*) Forschungsfragen formalisiert. Diese werden mittels qualitativer Forschungsmethoden, insbesondere der Fallstudienmethodik und Grounded Theory, adressiert. Ihre Anwendung fokussiert sich auf den Kontext der industriellen AF und entsprechend auf Industrien, in denen die AF bereits im industriellen Maßstab wertschöpfend zum Einsatz kommt (z. B. in der Luft- und Raumfahrtindustrie, Bahnindustrie, Automobilindustrie und im Maschinen- und Anlagenbau). Aufgrund gewählter induktiver Forschungsansätze ist der Erkenntnisgewinnungsprozess stark von den in diesem empirischen Kontext erhobenen Daten geprägt (z. B. aus Interviews, der Sichtung von Dokumenten und der Analyse von Webseiten). Darüber hinaus stützt sich diese Dissertation auf etablierte Theorien, darunter die Transaktionskostentheorie, der ressourcenbasierte Ansatz und die Konfigurationstheorie. Diese dienen dazu, die Ergebnisse zu diskutieren sowie Nuancen der Theorien herauszuarbeiten und für den Anwendungsfall der AF zu interpretieren.

Die vorliegende Dissertation ist kumulativ. Sie besteht aus vier Studien, welche den Hauptteil der Dissertation bilden. In zwei Teile gegliedert, Teil A und Teil B, werden die beiden adressierten strategischen Entscheidungsbereiche, die Geschäftsmodellentwicklung (Teil A) und die Wahl des Supply Chain Designs (Teil B), abgedeckt. Mit den beiden Teilen sind unterschiedliche Perspektiven verbunden. Hinsichtlich der Geschäftsmodellentwicklung für die AF befinden sich Logistikdienstleister (LDL) in einer kritischen Position. Der erwartete Wandel zu dezentralen, kürzeren Supply Chains greift ihr Kerngeschäft an und ihre hohe Kundenorientierung erfordert, dass sie sich an die mit der AF verbundenen Kundenbedürfnisse anpassen. In Teil A unterstellt **Studie A.1** eine prozessbasierte Perspektive, um ein umfassendes Verständnis dafür zu entwickeln, wie LDL auf die Breite an Technologien der AF (inklusive des konsumentenorientierten Polymer 3D-Drucks) mit spezifischen Aktivitäten reagieren. Die Studie entwickelt sechs Profile, die zeigen, wie LDL die AF sowohl als Anwender als auch als Entwickler von Services für externe Kunden nutzen. Als ein

zentrales Ergebnis von Studie A.1 zeigt sich, dass die initiierten Aktivitäten häufig stark auf den traditionellen Ressourcen von LDL basieren. Nur wenige LDL lösen ihre Aktivitäten von ihren traditionellen Geschäftsmodellen und entwickeln digitale, plattformbasierte Services für die AF. Im Gegensatz zu der prozessbasierten Perspektive und dem Fokus auf Geschäftsmodelldynamiken in Studie A.1, wird in **Studie A.2** eine Output-Perspektive eingenommen, um sechs generische Geschäftsmodellkonfigurationen für LDL in der industriellen AF zu entwickeln. Jede Konfiguration ergibt sich aus der Analyse der Perspektive der LDL und wird aus dem Blickwinkel potenzieller Partner/Wettbewerber und industrieller Kunden reflektiert. Die Passgenauigkeit der sechs Konfigurationen wird für bestimmte Typen von LDL untersucht und es erfolgt deren Einbettung in eine literaturbasierte Service Supply Chain für die AF. In Kombination entwickeln die Studien A.1 und A.2 ein umfassendes Verständnis dafür, wie LDL derzeit auf die AF reagieren und bieten eine empirisch fundierte Perspektive auf „fertige“ Geschäftsmodelle in der industriellen AF, um literaturbasierte Visionen zu reflektieren und zu verfeinern.

Teil B dieser Dissertation ist dem Mechanismus der (Um-)Gestaltung von Supply Chains für die AF gewidmet, der aus der Perspektive von fokalen produzierenden Unternehmen aufgrund ihrer dominanten Position in Supply Chains untersucht wird. Zur Charakterisierung von Supply Chain Designs für die AF werden zwei Dimensionen herangezogen: ihr horizontaler Umfang (geographische Verteilung) und ihr vertikaler Umfang (Governance-Struktur). Die Kombination beider Dimensionen ist geeignet, um die in der Literatur beschriebene Vision kürzerer, dezentraler Supply Chain Designs (horizontaler Umfang) mit erleichtertem Outsourcing an lokale Partner (vertikaler Umfang) zu erfassen. **Studie B.1** nimmt eine unternehmenszentrierte Perspektive ein, um ein tiefgreifendes Verständnis für Make-or-Buy-Entscheidungen für die AF von produzierenden Unternehmen zu entwickeln, deren Ergebnisse die Governance-Struktur von Supply Chains maßgeblich bestimmen. Die Studie verdeutlicht, wie die spezifischen (digitalen (*„digital“*) und aufkommenden (*„emerging“*)) Merkmale der AF die Argumente etablierter Theorien, welche Make-or-Buy-Entscheidungen im „analogen“ Zeitalter erklären können, modifizieren. Im Vergleich dazu geht **Studie B.2** von einer unternehmenszentrierten zu einer netzwerkbasierten Perspektive über, die sich auf beide Dimensionen stützt, um kohäsive Konfigurationen für Supply Chain Designs zu erforschen. Genauer gesagt untersucht Studie B.2 vier polare Konfigurationen und identifiziert die Beweggründe produzierender Unternehmen für deren Wahl. Auf diese Weise wird ein Bewusstsein dafür geschaffen, warum produzierende Unternehmen derzeit triftige Gründe dafür haben, die industrielle AF intern oder verteilt in einem sicheren, firmeneigenen Netzwerk zu implementieren. Die Verknüpfung beider Studien liefert ein Verständnis dafür, warum produzierende Unternehmen gegenwärtig bestimmte Governance-Strukturen für die industrielle AF wählen und sich für Supply Chain Designs entscheiden, die von der in der Literatur beschriebenen Vision einer dezentralisierten Fertigung und weitreichendem Outsourcing abweichen.

Insgesamt positioniert sich diese Dissertation als theorieorientierte Forschung, die gleichzeitig darauf abzielt, Managern von produzierenden Unternehmen und von LDL beim Treffen von fundierten Entscheidungen bei der Implementierung der AF in ihren Supply Chains und der Entwicklung von AF-basierten Geschäftsmodellen zu unterstützen. Die drei Studien A.1, A.2 und B.2 tragen zur initialen Theoriebildung bei, indem sie erörtern, wie und warum spezifische Geschäftsmodelle und Supply Chain Designs für die AF entstehen. Mit ihrem Fokus auf die Verständnisbildung für kausale Zusammenhänge (*wie* und *warum*) und mit ihren prozess- und outputbasierten Perspektiven ermöglichen es die Studien, auf der Basis der Kenntnis derzeitiger Reaktionen begründet, die zukunftsorientierten, hohen Erwartungen an die AF zu reflektieren. Infolgedessen bereichern und verfeinern die Studien den derzeitigen Wissensstand in der AF-Geschäftsmodellliteratur zu LDL und in der Operations- und Supply-Chain-Management-Literatur zu Supply Chain Designs mit einem Fokus auf deren geografische Verteilung und Governance-Struktur. Mit ihrer Einbettung in den industriellen Kontext der AF trägt diese Dissertation außerdem zum Aufbau von kontextspezifischen Erkenntnissen bei. Diese können als ein „Puzzleteil“ ein breiteres theoretisches Verständnis ermöglichen, wie die AF und andere digital geprägte (Produktions-)Technologien das Zeitalter von digitalen Geschäftsmodellen und Supply Chains gestalten werden. Insbesondere Studie B.1 zeichnet sich durch ihren Fokus auf die Auseinandersetzung mit bestehenden Theorien und das Ziel der Entwicklung einer kontextabhängigen Theorie („*middle-range theory*“) aus. Die Studie zeigt, dass etablierte Theorien im aufkommenden digitalen Umfeld der AF widersprüchliche Hinweise dazu liefern, ob der Produktionsprozess intern aufgebaut oder an Outsourcing-Partner ausgelagert werden sollte. Solche Erkenntnisse für die industrielle AF bieten zahlreiche Möglichkeiten für die zukünftige Forschung, darunter der Vergleich mit anderen Industriekontexten mit ähnlichen Charakteristiken und die Operationalisierung der in dieser Dissertation entwickelten Propositionen in quantitativen Modellen zur Entscheidungsunterstützung.

## Abstract

Recent global crises like the COVID-19 pandemic challenge traditional global supply chains (SCs). Their disaggregated, “fine-sliced” character comes with a high risk of disruption, and current supply bottlenecks (e.g., the chip shortage in the automotive industry) demonstrate that there is often no quick fix. Firms are increasingly under pressure to react and (re-)design their SCs to increase their resilience. Additive manufacturing (AM) technologies are acclaimed for their potential to foster the shift from global SCs to shorter, decentralized, and more resilient SCs. The key feature of AM technologies lies in their inherently digital and flexible nature. Their specific characteristics are envisioned to enable location-independent manufacturing close to or even at the point of demand and lead to a commoditization of manufacturing infrastructure for flexible outsourcing to local partners. Moreover, AM technologies are expected to revolutionize the way firms do business and put traditional business models at stake.

This doctoral thesis is motivated by the outlined potential of AM and the resulting impact on firms' supply chain design (SCD) and business model choices. The extant literature raises high expectations for AM. However, concrete and real-world insights from specific application domains are still scarce. This thesis seeks to fill the gap between high-level literature-based visions and currently emerging realistic business models and SCDs for AM. Thereby, AM is understood as a potential intervention emanating from outside firms and requiring them to react by realigning their business models and SC structures to maintain a *fit*. This thesis aims to build an in-depth understanding of these mechanisms and, hence, of the inner causal processes involved in the AM SCD and business model choices. This concentration on the rationales and underlying behavioral patterns is formalized with primarily exploratory (*how* and *why*) research questions that are addressed with qualitative research methodologies, mainly case study research and grounded theory. These methodological practices are applied in the industrial AM context, entailing an embedding of this thesis in challenging industries where AM applications have already started to create value (i.e., in the aerospace, rail, automotive, and machinery and equipment industries). The selected research approaches are mostly inductive and, hence, strongly driven by the data collected from this context (e.g., in interviews, by reviewing documents, and by analyzing websites). Additionally, this thesis relies on grand theories, namely transaction cost economics, the resource-based view, and configuration theory, to discuss the findings in their light and to interpret and distill nuances of these theories for their application in the industrial AM context.

This thesis is cumulative, consisting of four studies that form its main body. These studies are organized in two parts, part A and part B, since two domains of strategic decisions are targeted jointly, the business model development (part A) and AM SCD choice (part B) for industrial AM. Different perspectives are associated with the two parts. Logistics service providers (LSPs) are in a critical position to develop AM business models. Based on the expected shift to decentralized, shorter SCs, the traditional business models of LSPs are at risk, and their inherent customer orientation puts them under pressure to adjust to their customers' needs in AM. In part A, **study A.1** applies a process-based perspective to build a broad understanding of how LSPs currently respond to AM and consumer-oriented polymer 3D printing with specific AM activities. It proposes six profiles of how LSPs leverage AM, both as users for their in-house operations and as developers of AM-specific services for external customers. A key finding is that the initiated AM activities are oftentimes strongly based on LSPs' traditional resources. Only a few LSPs are found whose AM activities are detached from their traditional business models to focus on digital platform-based services for AM. In contrast to the process-based perspective and focus on business model dynamics in study A.1, **study A.2** takes an output perspective to propose six generic business model configurations for industrial AM. Each configuration emerges from the perspective of LSPs and is reflected by their potential partners/competitors and industrial customers. Study A.2 explores how the six generic configurations fit specific types of LSPs and how they are embedded in a literature-based service SC for industrial AM. In combination, studies A.1 and A.2 provide a comprehensive

understanding of how LSPs are currently reacting to AM and an empirically grounded perspective on “finished” AM business models to evaluate and refine literature-based visions.

Part B of this thesis is devoted to the mechanism of (re-)designing SCs for AM, which is investigated from the perspective of focal manufacturing firms based on their dominant position in SCs. Two dimensions are used to characterize AM SCDs, their horizontal scope (geographic dispersion) and vertical scope (governance structure). The combination of both dimensions is ideally suited to capture the literature-based vision of shorter, decentralized AM SCs (horizontal scope) with eased outsourcing to local partners (vertical scope). **Study B.1** takes a firm-centric perspective to develop an in-depth understanding for AM make-or-buy decisions of manufacturing firms, the outcomes of which determine the SC governance structure. This study elaborates how the specific (digital and emerging) traits of industrial AM technologies modify arguments of grand theories that explain make-or-buy decisions in the “analog” age. In comparison, **study B.2** shifts from a firm-centric to a network perspective to rely on both dimensions for investigating cohesive AM SCD configurations. More specifically, study B.2 explores four polar AM SCD configurations and reveals manufacturing firms’ rationales for selecting them. Thereby, it builds an understanding for why manufacturing firms currently have valid reasons to implement industrial AM in-house or distributed in a secure, firm-owned network. As a result, combining both studies provides an understanding of why manufacturing firms currently select specific governance structures for industrial AM and opt for SCDs that differ from the literature-based vision of decentralized, outsourced AM.

Overall, this thesis positions itself as theory-oriented research that also aims at supporting managers of manufacturing firms and LSPs in making informed decisions when implementing AM in their SCs and developing AM-based business models. The three studies A.1, A.2, and B.2 contribute to initial theory building on how and why specific AM business models and SCDs emerge. With their focus on developing an understanding for the causal processes (*how* and *why*) and by assuming a process-based and output perspective, they can draw a line from firms’ current reactions to sound reflections on future-oriented, high-level expectations for AM. As a result, the studies significantly enrich and refine the current body of knowledge in the AM business model literature on LSPs and the operations and supply chain management literature on AM SCDs, focusing on their geographic dispersion and governance structure. This thesis further contributes with its context-specificity to building domain knowledge for industrial AM, which can serve as one “puzzle piece” for theorizing on how AM and other digitally dominated (manufacturing) technologies will shape the era of digital business models and SCs. In particular, study B.1 stands out by its focus on theory elaboration and the objective of developing contextual middle-range theory. It reveals that emerging digital AM is a setting where the argumentation of grand theories provides contradicting guidance on whether to develop AM in-house or outsource the manufacturing process. Such findings for industrial AM raise multiple opportunities for future research, among them are the comparison with other industry contexts with similar characteristics and the operationalization of the propositions developed in this thesis in follow-up quantitative decision-support models.

## Content overview

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## List of abbreviations

| | |
|---|---|
| 2PL | Second-party logistics service provider |
| 3PL | Third-party logistics service provider |
| 4PL | Fourth-party logistics service provider |
| AM | Additive manufacturing |
| CAD | Computer-aided design |
| CAM | Computer-aided manufacturing |
| CEP | Courier-, express-, parcel- |
| DM | Distributed manufacturing |
| IP | Intellectual property |
| LM | Logistics management |
| LSP | Logistics service provider |
| MRO | Maintenance, repair, and operations |
| MRT | Middle-range theory/middle-range theorizing |
| OEM | Original equipment manufacturer |
| OM | Operations management |
| OSCM | Operations and supply chain management |
| PPAP | Production part approval process |
| RBV | Resource-based view |
| SC | Supply chain |
| SCD | Supply chain design |
| SCM | Supply chain management |
| SME | Small and medium-sized enterprise |
| STL | Surface tessellation language/standard triangle language |
| TCE | Transaction cost economics |

# 1 Introduction

It was in 1988 when S. Scott Crump produced his first 3D print – a toy frog for his daughter – by using a 2D plotter, a hot glue gun, and different materials, including candle wax (Beltagui et al., 2020). This was the birth of Fused Deposition Modeling, the process that accounts for the largest installed base of additive manufacturing (AM) machines today (Wohlers Associates, 2021b). Around the same time, Charles Hull developed a process that is known as Stereolithography. He founded the firm 3D Systems and made the first Stereolithography-based machine available for commercial use in 1987 (Ngo et al., 2018; Wohlers Associates, 2021a). The development of these first AM technologies in the late 1980s marked the tentative beginning of a new digital manufacturing era. Today, AM has evolved into one of the most discussed topics in manufacturing technologies and is attested to have disruptive potential in many fields. For example, private households can nowadays use compact polymer 3D printers at home to print gadgets, and the public witnessed the most likely lifesaving use of AM for personal protective equipment at the outbreak of the COVID-19 pandemic in the spring of 2020 (Feldman, 2020). But AM goes far beyond consumer-oriented operations and is starting to become a set of mainstream manufacturing technologies for industrial applications. The technologies are fundamentally different from traditional manufacturing. Former US President Obama even predicted in 2013 that AM technologies have the "potential to revolutionize the way we make almost everything" (CNN, 2013). Equally large are the expectations that AM technologies will bring a revolution to the way firms do business and "shake-up" the design of supply chains (SCs) (Ghobadian et al., 2020; Holmström et al., 2016).

This doctoral thesis focuses on the industrial side of AM technologies. It contributes to the development of an empirically grounded understanding of *how* and *why* AM impacts firms' business model development and strategic supply chain design (SCD) choice. The main body of this thesis consists of four studies that have been published in scientific journals. The following sections aim at introducing and framing the objective and detailing a roadmap for this thesis. In Section 1.1, as a research motivation, reasons are provided as to why it is expected that AM will impact incumbents' business models and drive SCD changes. Section 1.2 then presents the addressed research gaps. In Section 1.3, these serve as a basis for deriving the research objective and overarching research questions that guide this thesis. Section 1.4 summarizes the selected research designs of the four studies and highlights the overall theoretical contribution. Finally, Section 1.5 outlines the structure of this thesis.

## 1.1 Research motivation

Since their introduction in the late 1980s, AM technologies have developed in leaps and bounds. The expiration of key patents has fueled technological development, as reflected in the number of patents. For example, the European Patent Office (2020) identified a total of 21,616 submitted patent applications in the context of AM between the years 2000 and 2018, making AM one of the top fields in which firms are driving innovation. New AM-specific actors have grown the market to commercialize AM equipment (e.g., machines, materials, and software and platform solutions) and to develop AM-specific services (Holzmann et al., 2020a; Holzmann et al., 2020b; Rogers et al., 2016). Simultaneously, manufacturing firms from pioneering industries have started to adopt AM technologies and integrate them into their SCs. As a reflection of the increasing implementation in industry, Ernst & Young found in a cross-industry survey that 65% of the 900 participating firms have started to gain experience in AM (EY, 2019). Similarly, the 2021 annual AM report of Sculpteo indicated that nearly two-thirds (61%) of more than 1,900 surveyed users of AM intended to increase their investments and, hence, their engagement in AM (Sculpteo, 2021).

This thesis is concerned with **industrial AM**, the professional application of AM technologies in industries. Industrial AM is primarily used to produce metal and high-quality polymer applications. Gartner (2019, p. 36) uses the term enterprise 3D printing in a similar vein to refer to the use of

AM for "product design, development and prototyping, […] in manufacturing processes to produce tools, jigs and fixtures, and to the production of finished goods." Industrial AM differs in terms of achievable product quality, applicable materials, and investment intensity from polymer 3D printing, which denotes the famous, less demanding consumer side of AM technologies (Thomas-Seale et al., 2018).

But what is so revolutionary about AM for industrial applications? At first glance, AM technologies create **new freedom of design** for engineers by facilitating bionic constructions, lattice structures, and functional optimization (Fontana et al., 2019; Orme et al., 2017). Engineers can manufacture lightweight parts with increased stiffness, complex shapes, and internal geometries that are unattainable using traditional manufacturing technologies (Olsen & Tomlin, 2020). For example, the Airbus A350 XWB aircraft contains more than 1,000 additively manufactured new parts, reducing the overall weight and ensuring more fuel-efficient flight operations (Krassenstein, 2015). Similarly, the automotive manufacturer Bugatti achieved with the first additively manufactured titanium brake caliper a weight reduction of about 40%, while ensuring a higher stress resistance than with traditionally manufactured ones (Bugatti, 2018). Another famous example is General Electric, which has been using AM in serial production for its LEAP aircraft engine's fuel nozzle tip. In fact, traditional manufacturing was not able to create the complex inner geometry of the walnut-sized piece that is key to the engine's efficiency. AM simplifies the manufacturing process, reducing the 20 parts initially required for a fuel nozzle tip down to manufacturing only a single functional part that is five times more durable and 30% more cost-efficient (Kover, 2018). An even greater reduction in the number of manufactured parts was achieved for the Ariane 6 rocket. For the injector head of the rocket engine, 248 parts were integrated into one by means of AM, resulting in a significant reduction in the production costs (~50%) and production time (EOS, 2022).

The examples demonstrate that the new freedom of design is groundbreaking for achieving superior designs (e.g., weight reductions and functional integration), efficiency gains in production, and more sustainable operations in the life cycle of products compared to traditional subtractive manufacturing technologies. However, the essential game changer for the operations and supply chain management (OSCM) communities lies in the **digital character of AM technologies**. AM parts are digitally specified – all the manufacturing information is encapsulated in the digital design file (Ben-Ner & Siemsen, 2017; Massimino et al., 2018). This enables the manufacturing of parts directly from the digital design file in a process that does not depend on product-specific setup and is tool-free. As a consequence, AM machines are inherently flexible for the to-be-manufactured design. For this reason, they are also coined as general-purpose equipment (Holmström et al., 2016). Ideally, the design file can be electronically transferred to any AM machine and manufactured in a one-step process (Hedenstierna et al., 2019). The AM machine itself has low space requirements, is transportable, and only relies on basic raw materials (Mellor et al., 2014). Moreover, the skill requirements for operating AM machines are comparatively low, and the AM process chain is becoming increasingly automated, which is expected to make AM technologies widely accessible, even for non-specialists (Ben-Ner & Siemsen, 2017).

Based on its inherently digital and flexible nature, industrial AM is touted for its potential in several ways: for reducing upfront production costs, enhancing the speed to market of new product development, and enabling economic, small-scale manufacturing (Ben-Ner & Siemsen, 2017; Rayna & Striukova, 2016b). These benefits of AM are expected to lead to fundamental changes of the paradigm of traditionally centralized mass production that has been dominant in many industries for decades (Verboeket & Krikke, 2019). AM is said to enable a shift from centralized manufacturing to **distributed, small-scale manufacturing** close to or even at the point of demand (Kumar et al., 2020). In the global context, decentralized, small-scale AM has the potential to contribute to the trend of reshoring manufacturing activities from low-cost countries back to Europe and the US (Laplume et al., 2016). Recent SC disruptions caused by the COVID-19 pandemic, natural disasters, geopolitical conflicts, and cyberattacks have sparked the discussion of reshoring (e.g., Mariotti, 2022; Roscoe et al., 2022). The resulting supply bottlenecks are currently forcing firms to react and increase the resilience of their SCs (McKinsey, 2020). For example, from among 23 industries, McKinsey (2020) found that SC disruptions can eliminate on average 40% of a firm's yearly profits every decade. Based on these financial losses, they predict in a five-year time span (2020–2025) a relocation of production in up to 25% of the global value chains of highly exposed industries. Such industries are characterized by their trade intensity and export concentration in a few countries (e.g., communication equipment, computers and electronics, and semiconductors) as well as by their labor intensity (e.g., apparel). For Germany, a similar development is on the horizon. In the recent 2022 spring "AHK World Business Outlook," 34% of the more than 4,200 surveyed firms[1] expected to critically put their location decisions to test, 22% to relocate their manufacturing activities, and 16% to establish their new locations closer to the German or European home market. Moreover, 27% of the surveyed firms expected to diversify their suppliers (Deutscher Industrie- und Handelskammertag, 2022).

Indeed, decentralized, small-scale AM is currently starting to demonstrate its benefits for specific applications, in particular, for **(uptime-critical) spare parts**. For instance, the rail industry is in the process of installing AM machines at maintenance plants. Sending the digital files to these AM machines to manufacture on-demand from scratch has significantly improved the availability of the spare parts and bypassed lengthy lead times (Sertoglu, 2021). In addition, AM enables railway operators like Nederlandse Spoorwegen and Deutsche Bahn to resolve obsolescence problems and reduce their inventory based on the avoidance of minimum order quantities (Deutsche Bahn, 2022; DiManEx, 2018a). Similarly, Daimler Buses has reportedly additively manufactured more than 40,000 spare parts and invested in a transportable AM micro-factory to evaluate the potential of decentralizing AM to increase the speed of supplying spare parts. In theory, the AM micro-factory can be flexibly placed at the point of demand for ad-hoc manufacturing of high-quality spare parts (Mercedes-Benz, 2022). Moreover, mobile AM units have already been tested at remote or isolated locations with intermittent spare part demand, such as military and humanitarian missions, on board sea vessels, and even at the International Space Station (Judson, 2020; Krassenstein, 2014; Made in Space, 2019). The French and the Dutch armed forces, for example, have been using polymer 3D printing to produce spare parts at far-off bases for the UN Peacekeeping Mission in Mali (3dprinting.com, 2019; DiManEx, 2018b).

This doctoral thesis is motivated by the outlined **potential and consequences** of emerging and inherently digital AM technologies **for incumbent firms' operations**. Manufacturing firms for components and end products, retailers, and logistics service providers (LSPs) are coined as typical incumbents that have established their products and services in the traditional manufacturing market and found a competitive position in traditional SCs where their operations are embedded. Multiple incumbent firms are currently getting involved with industrial AM. However, while there are novel technologies that firms can suitably integrate into their existing business models and existing structures, the examples above suggest that AM is likely to necessitate different ways of doing business and different SCDs. This thesis is concerned with incumbents' business model development and SCD choice for industrial AM. This focus requires studying two domains of strategic decisions jointly, positioning this thesis at the interface of business model research and OSCM research for industrial AM: From the perspective of business model research, a business model reflects a firm's competitive strategy and is manifested in a firm's choice of activities (Casadesus-Masanell & Zhu, 2013). Leveraging the radically different characteristics of AM compared to traditional manufacturing technologies is expected to require incumbent firms to question or even reinvent their existing business models (Bogers et al., 2016). In this sense, this thesis understands AM as a threat for incumbent firms' existing activity system, but also as an opportunity for new activities that enable firms to create and capture value from AM. Analogously, from the perspective of OSCM research, SCs are structures that enable firms to achieve their competitive strategies. A

[1] The sample includes worldwide operating German firms, branches and subsidiaries, as well as firms with close ties to Germany.

SC that is designed for and aligned with the competitive strategy of a firm should be able to provide the desired outcome to customers and give the firm an edge over its competitors, for example, by supplying products at lower costs or superior (service) quality (Hofmann, 2010; Ketchen & Hult, 2007). In this thesis, AM is understood as a driver for incumbent firms to adapt or completely change their traditional SCD.

In order to investigate both the AM business model development and AM SCD choice, the concept of ***fit*** (Doty et al., 1993) is a central element of this thesis. Industrial AM as a set of inherently digital and emerging technologies represents an external source of *misfit* for firms' established competitive strategies and structures. As a reaction, firms may reactively adapt to create fit or proactively influence the AM industry and institutional environment to fit their strategies and structures (Van de Ven et al., 2013). With such an underlying understanding of industrial AM as a potential source of misfit, this thesis enriches the growing stream of literature on AM business model development and AM SCD. The purpose of this thesis is specified in more detail by presenting the addressed research gaps leading to the research objective, the overarching research questions, and its main contribution in the next three sections.

## 1.2 Addressed research gaps

Prompted by the increased relevance of AM among practitioners, the topic has also gained **momentum in academia**. Figure 1-1 depicts the search volume for the term "additive manufacturing" since January 2004 based on the search engine "Google" (Google Trends, 2022). The y-axis demonstrates the frequency of searches indexed with 100 as the peak of the search volume (number of searches). As shown in Figure 1-1, public interest in AM is not entirely new but has grown in the last two decades. Web searches started to become significant from 2013/2014 on, marking the peak of the consumer 3D printing hype. With growing public awareness, researchers also became interested in AM. As illustrated in Figure 1-1, the number of scientific publications (number of search results) identified with a full-text search for "additive manufacturing" in the database "Google Scholar" has climbed and is continuing to do so.

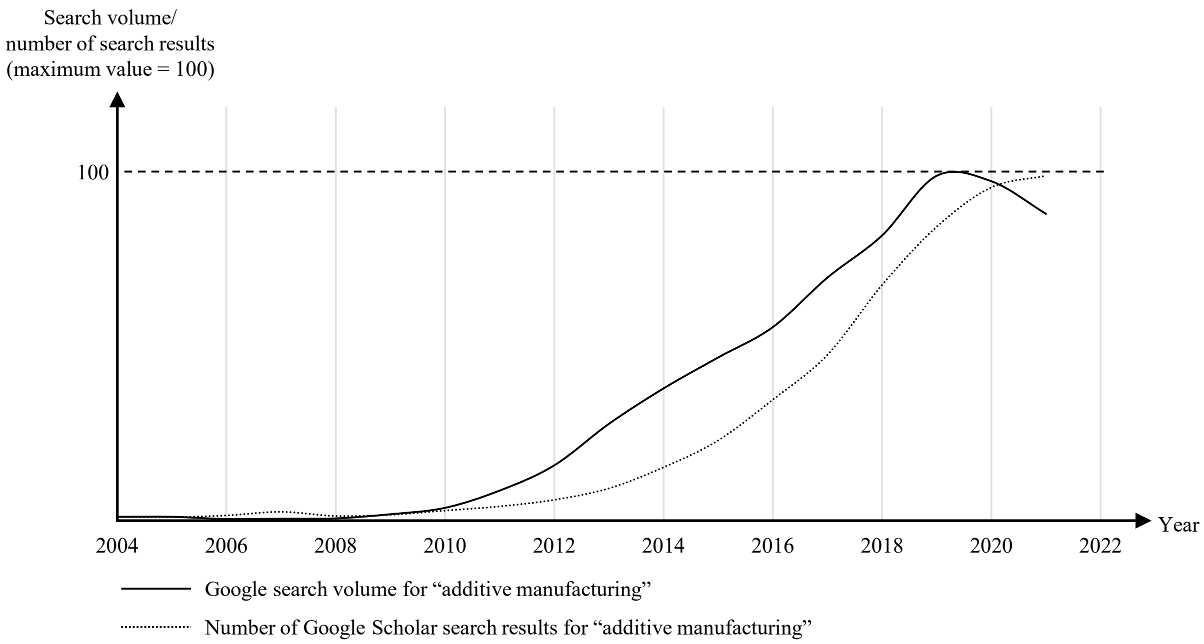



Figure 1-1: Google search volume and number of Google Scholar search results.

With the rapidly growing research field of AM comes the challenge of a high number of disjoint studies. Caviggioli and Ughetto (2019) identified in a bibliometric analysis that the **body of literature** dealing with AM is still immature and fragmented. Their results indicate that AM studies are published across a variety of outlets, while the overall AM citation network is based on only a few key authors as central nodes and lacks connectivity between authors. When focusing on the units of analysis in existing studies, three tendencies are striking: First, a significant amount of early research has been devoted to the technological development of AM machines and materials (Caviggioli & Ughetto, 2019; Öberg et al., 2018). Corresponding studies from the engineering domain investigate the activity (i.e., the AM process) and required resources. These studies provide insights into what AM yields in terms of product and process innovation but less from a business model or SC perspective (Rayna & Striukova, 2016b). Second, there is currently a strong emphasis on the (disruptive) potential of AM, resulting in general, high-level expectations for AM, as emphasized by Maresch and Gartner (2020). For example, several studies provide visions of how AM can transform the business landscape and design of SCs, leading to economic, social, and organizational consequences (e.g., Ben-Ner & Siemsen, 2017; D'Aveni, 2015; Ghobadian et al., 2020). Such general expectations come with the risk of being "exaggerated" (Glas et al., 2021, p. 495) and, hence, unable to capture the realistic potential of AM. Third, several studies do not investigate AM specifically but summarize AM and other digital technologies that all contribute to the idea of Industry 4.0. Among them are blockchain technology, robotics and advanced automation, artificial intelligence, and the Internet of Things. Industry 4.0 promotes a new industrial revolution empowered by the ability of the aforementioned technologies to enable real-time connections between the physical and digital domains (Olsen & Tomlin, 2020). Studies from the Industry 4.0 realm expect the sum and interplay of these technologies to drive far-reaching changes in industries by fostering digitalization, customization, and local production (Kumar et al., 2020). However, they provide limited insights into AM specifically.

In light of the identified trends in the literature – the focus on technological aspects, the high-level expectations for AM, and the discussion under the Industry 4.0 terminology – the understanding of how incumbents respond and adapt to AM remains scarce for now. Most significantly, AM currently confronts incumbent firms with **challenges** that must be overcome in real-world applications when integrating AM into business models and designing SCs for AM: In a nutshell, industrial AM technologies are currently in an emerging stage (Rong et al., 2018) and, therefore, come with a high risk of obsolescence and uncertainty as to which technologies will prevail. As a result, firms may put their commitment and investment decisions at stake since technologies may be outdated fast. Moreover, AM technologies are currently evolving in a nascent, fast-developing market, which can be characterized as an unstructured setting with extreme ambiguity (Santos & Eisenhardt, 2009). Competitive positions are not fully established, and relationships are still unstable, which confronts firms with the question of whether and how to position themselves in AM. Based on the digital characteristics of AM, traditional relationships, roles, and distinctions between products and services may become blurred and challenge firms to operate outside their traditional comfort zone. In addition, the digital characteristics of AM pose novel risks of leakage of firms' digitally encapsulated know-how (Holmström et al., 2019). Among others, firms are confronted in their AM implementation with the need for secure digital infrastructure and IT solutions for protecting their digitally specified intellectual property (IP) (Bechtold, 2016). Finally, firms, in particular small and medium-sized enterprises (SMEs), may not even be aware of the potential of AM or capable of taking advantage of the technologies due to their lack of knowledge and organizational readiness (Martinsuo & Luomaranta, 2018).

As a result of these obstacles, AM business models and AM SCDs are oftentimes not yet fully established. For now, the demand of industrial customers and the required competencies to satisfy the demand remain uncertain, and firms do not have the expertise and sufficient scales of applications to justify technological investments, which reduces the dissemination of AM (Rong et al., 2018). Hence, there are many industrial applications where practice does not meet the general expectations from literature yet. As a consequence, firms may implement AM exactly or in a similar way to how they have implemented traditional manufacturing technologies for decades and, thus, miss the chance to leverage the potential of the technologies, as also noted by Klöckner et al. (2020). To reduce the **discrepancy between the expectations from literature and practice**, there is a need to establish links between the high-level expectations and specific application domains, as also suggested by Maresch and Gartner (2020). In a similar vein, several studies point to a need for more context-specific and, thus, industry-specific research on AM (Ford & Despeisse, 2016; Hohn & Durach, 2021; Rehnberg & Ponte, 2018). With such "deep dives," a richer understanding of the impact and implications of AM can be gained and drive advances at the current exploratory stage of AM research (Ford & Despeisse, 2016).

The outlined discrepancy between expectations voiced in the literature and industrial practice is also visible in the more specific streams of literature dealing with AM business models and AM SCDs. While the background literature will be investigated in detail in Chapter 2, the following two paragraphs provide a brief overview and concretize the relevant research gaps for this thesis:

The **AM business model literature** strongly argues for the disruptive effects of AM on incumbents' business models and raises expectations of how incumbents can position themselves in industrial AM. These expectations for incumbents are mostly conceptually derived and provide a static picture. More specifically, the literature postulates visions of "finished" business models of incumbent firms in industrial AM: For manufacturing firms, the characteristics of AM are expected to transform their business models from centralized to decentralized (Durach et al., 2017b), from product-oriented to integrated product-service systems (Savolainen & Collan, 2020a), and from closed to open (Bogers et al., 2016). Moreover, the reputation of AM as digital technologies that rely on easy-to-acquire production skills and increasing automation leads to the expectation that retailers and LSPs – as traditional non-manufacturers – will become active in AM (Arbabian & Wagner, 2020; Durach et al., 2017b). Particularly pronounced is the vision of LSPs to turn into manufacturers for AM by leveraging their decentralized warehouses or distribution centers to offer manufacturing as a value-added service to their industrial customers (e.g., Pause & Marek, 2019; Wieczorek, 2017). Such conceptually derived and static visions of incumbents' business models in AM currently lack empirical evidence. In this sense, Savolainen and Collan (2020a, p. 1) term AM business model research "an emerging area of research, where tangible, case-based evidence is still rare." Moreover, they call the literature-based views on the business potential of AM "strongly divided" and "scattered" (Savolainen & Collan, 2020a, p. 1 & p. 3), and Holzmann et al. (2020a) as well as Holzmann et al. (2020b) assess the knowledge on AM business models as insufficient. In addition, the static output perspective on visions of "finished" AM business models reveals that there is a lack of studies that take a process-based perspective to explore how incumbents are currently reacting to AM and gradually adapting their existing business models. As a further consequence, previous work does not sufficiently consider if and how AM-specific services and products relate to and interact with the traditional business models of incumbents like, for example, LSPs' established logistics services. In this vein, Rong et al. (2018, p. 235) term the emergence of AM business models a "culmination of an iterative process," and indicate that this process and its interactions have not been sufficiently explored yet.

From a SC perspective, the **OSCM literature** suggests a simplified SCD for AM. This design contrasts traditional, global, and long SCs, which are known for their crossing of multiple national boundaries and involvement of multiple parties. By enabling decentralized, small-scale production, AM SCs are expected to become shorter, less complex, and more resilient (Holmström et al., 2010; Tziantopoulos et al., 2019; Verboeket & Krikke, 2019). Hence, AM SCs are anticipated to significantly shrink in their geographic scope. Visions include design files being stored in a digital warehouse, sent to AM machines that are located close to or even at the point of demand, and manufactured by generic service providers, termed AM service bureaus. The ease of transferring, sharing, and reusing the digital files with partners in the SC and the flexibility of AM machines as general-purpose equipment are the cornerstones of the envisioned simplified SCD. As stated by Verboeket and Krikke (2019, p. 92), "data files travel more easily than tangible products." Hence, data flows specifying digital products are expected to substitute the physical flows and databases (or "digital warehouses") the physical stocks of products at different stages in the SC. Moreover, the digital characteristics of AM are considered to be ideal for outsourcing manufacturing operations (Hedenstierna et al., 2019). For example, Berman (2012, p. 158) calls the "ability to easily share designs and outsource manufacturing" an essential advantage of AM compared to traditional manufacturing technologies. By flexibly and dynamically outsourcing the AM process to AM service bureaus, AM SCs are predicted to exhibit a low degree of vertical integration. However, in practice, it is striking that an AM-based transformation of traditional SCs is not happening on a significant scale yet (Prendeville et al., 2016). The tendency is for decentralized AM to be tested in specific settings (e.g., at remote locations like military missions) and for specific applications (e.g., uptime-critical spare parts). Moreover, other SCDs are currently emerging rather than the anticipated decentralization and extensive outsourcing, as this thesis will show. A few studies are aware of the slow transformation of SCs and argue that the development of AM SCs is a long-term process (Durach et al., 2017b; Holmström et al., 2016; Verboeket & Krikke, 2019). In this vein, Fawcett and Waller (2014, p. 159) acknowledge that "additive technologies are not going to revolutionize supply chain design overnight." Nevertheless, apart from the strong visions, there is a lack of research exploring how and why firms select suitable SCDs and which AM SCDs currently evolve considering the theoretical expectations of increased decentralization (characterizing the horizontal scope of SCs) and extensive outsourcing (characterizing the vertical scope of SCs).

## 1.3 Research objective and overarching research questions

Based on the overview of the state of AM research in general and the visions for incumbents' AM business models and SCDs in specific, this thesis contributes to filling the research gap between literature-based expectations and currently emerging, realistic business models and SCDs in the specific domain of industrial AM. It is devoted to providing a "deep dive" into the underlying causal mechanisms that drive incumbents in their reactions and strategic decisions with respect to AM. In addition, it seeks to find a balance between theorizing and deriving practically relevant results. To achieve this, the **overall objective** of the research presented in this thesis is twofold: First, it aims to build an in-depth understanding (*how* and *why*) of the impact of AM on two domains of strategic decisions of incumbents, the AM business model development and the SCD choice. Second, this thesis aims to offer decision support for practitioners that are in the process of implementing industrial AM in their operations. By demonstrating the advantages and risks associated with specific AM business models and SCDs, this thesis intends to provide managers with a clear perspective to make informed decisions.

The overall research objective defines the **scope** of this thesis: The focus lies on industrial AM. Findings are directly associated with industrial AM and not with broader digital technologies summarized under the Industry 4.0 terminology. The targeted decisions of this thesis, the AM business model and SCD choice, are essential elements of firms' AM implementation process. Firms that develop AM business models or adjust their SCDs to accommodate AM have already opted to adopt AM or at least get involved with the technologies. Hence, this thesis does not investigate their preceding AM adoption decisions (i.e., AM versus traditional manufacturing technologies) but focuses on crucial decisions taken on their AM implementation paths. Among incumbent firms, this thesis focuses on the strategic decisions of manufacturing firms and LSPs. Manufacturing firms are predestined users of AM and are structurally positioned in the center of SCs (Choi & Krause, 2006). Therefore, manufacturing firms – including component and end-product manufacturers – are understood as the dominant actors in industrial SCs that primarily determine the SCD for their products, as will be detailed in Section 2.3.1. As a result of this focal position of manufacturing firms in SCs, this thesis investigates AM SCD decisions from their perspective. Manufacturing firms' selected AM SCDs have immense implications for their outsourced logistics functions. LSPs are commonly contracted by manufacturing firms and other SC actors to provide logistics (e.g., transportation, warehousing, transshipment) and value-added services (van Laarhoven et al., 2000). With manufacturing firms (re-)designing their traditionally global SCs to shorter, decentralized SCs based on AM, the core of LSPs' business models is at risk (Durach et al., 2017b; Hofmann & Osterwalder, 2017; Holmström et al., 2010; Wieczorek, 2017). Several studies emphasize that LSPs must get active in AM and move their business into the era of digital SCs to stay competitive (e.g., Cichosz et al., 2020; Hofmann & Osterwalder, 2017). The direct dependence of LSPs on manufacturing firms' decisions and threatening confrontation with AM makes it interesting to explore how AM impacts their business model development. Therefore, this thesis focuses on the investigation of AM business models from the perspective of LSPs. To formalize the research objective within the outlined scope, this thesis is guided by two overarching research questions:

**RQA:** *How* and *why* does industrial AM impact the business model development of LSPs?

**RQB:** *How* and *why* does industrial AM impact the SCD choice of manufacturing firms?

The overarching research questions are addressed in four studies that form the main body of this thesis. RQA is addressed in the studies A.1 and A.2, while RQB is targeted in the studies B.1 and B.2. Figure 1-2 details how the two overarching research questions are concretized with specific sub-research questions within each of the four studies. In the following, the four studies are briefly characterized and distinguished from each other.

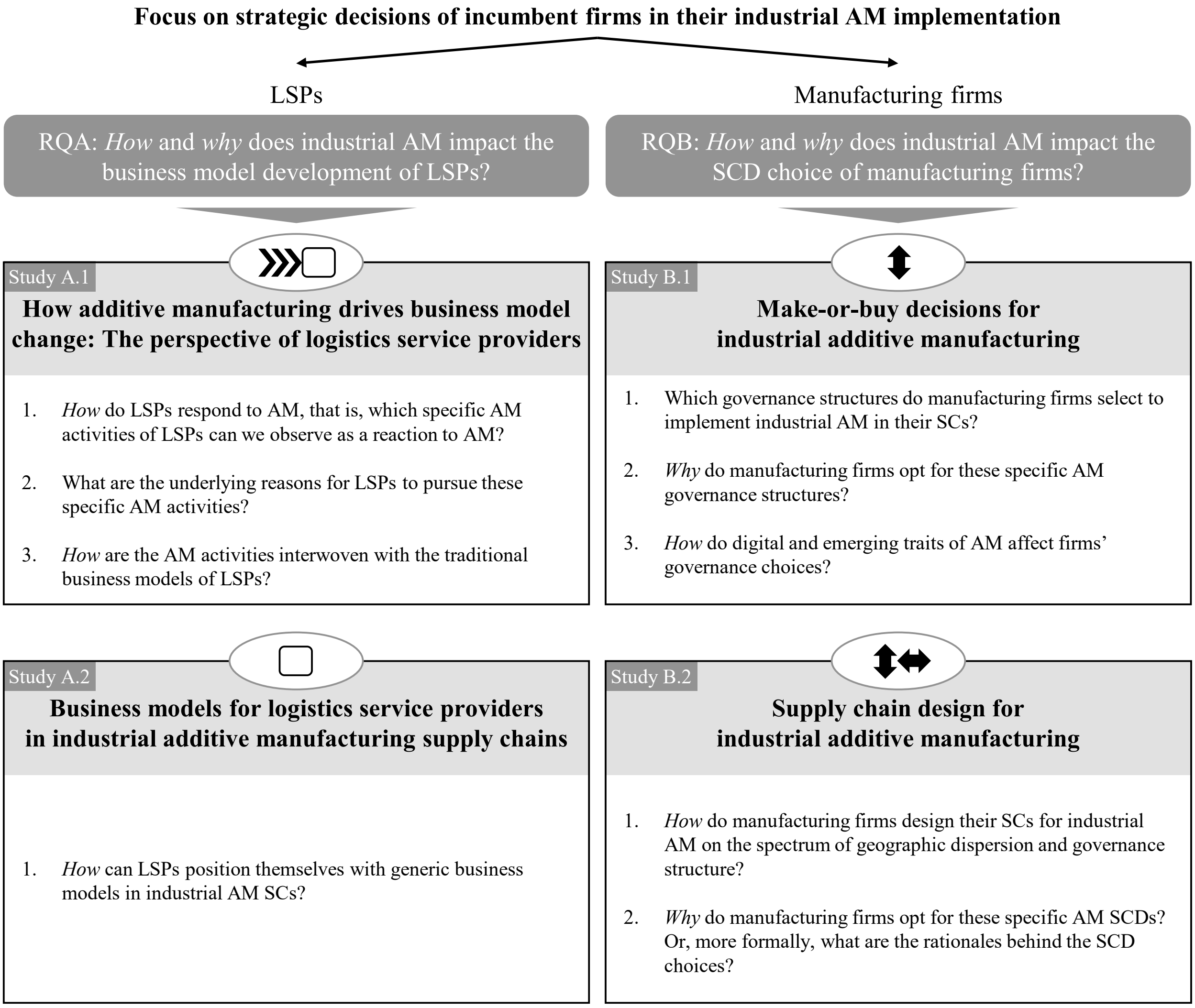



Figure 1-2: Overview of the overarching and study-specific research questions of this thesis.

To address the **AM business model development of LSPs (RQA)**, this thesis takes a process-based perspective in study A.1, which is complemented with an output perspective in study A.2. To be more specific, study A.1 aims to explore the business model dynamics of LSPs, thus, how LSPs are currently changing their existing business models as a response to AM. It provides a comprehensive picture and a profound understanding by classifying the AM activities of 47 LSPs. Based on this overview of AM activities, the focus of study A.1 lies on deriving the underlying reasoning of why the service-based logistics industry reacts to AM and on exploring how LSPs' AM activities interact with the traditional business models of LSPs. While study A.1 considers the full spectrum of AM activities that are observable for all types of LSPs (e.g., also in the field of consumer-oriented polymer 3D printing), study A.2 narrows its focus. Study A.2 concentrates on industrial AM and, for this reason, only considers types of LSPs that serve industrial customers. Moreover, study A.2 is future-oriented in contrast to the timeline of past and present AM activities that are explored in study A.1. While study A.1 takes a process-based perspective to explore how AM activities initiate dynamics of existing business models, Study A.2 takes an output perspective and targets the development of "finished" AM business models of LSPs. It develops generic configurations of business models that should enable LSPs to create value for their industrial customers and generate incoming revenue streams from AM. Six generic business model configurations are proposed. They form the basis for an interpretation with a business model lens and for reasoning on their fit for specific types of LSPs. Study A.2 further embeds the generic configurations in the context of the industrial AM service SC, reflecting the different perspectives in the SC (e.g., from potential partners/competitors and customers of LSPs). In contrast, study A.1 is closely tied to systematizing the AM activities and resulting business model dynamics of LSPs from their specific perspective. Table 1-1 summarizes the described characteristics of the studies A.1 and A.2.

Table 1-1: Characterization of the studies A.1 and A.2.

| | Study A.1 | Study A.2 |
|---|---|---|
| **Focus** | Dynamics of existing business models | Development of AM business models |
| **Addressed incumbents** | All types of LSPs | LSPs that serve industrial customers |
| **Perspective of investigation** | Process-based perspective (how traditional business models change as a response to AM) | Output perspective ("finished" AM business models that are expected to enable LSPs to create and capture value from AM) |
| **Purpose of investigation** | Comprehensive overview of the reactions of LSPs to AM; exploration of the interweaving of AM activities and traditional business models | Development of generic AM business model configurations; interpretation with a business model lens and reasoning for their fit for specific types of LSPs |
| **Temporality** | Past-/present-oriented | Future-oriented |
| **AM context** | Industrial AM and consumer 3D printing | Industrial AM for industrial customers |
| **Consideration of the AM context** | - (closely tied to the perspective of LSPs) | Embedding of business models in the AM service SC |

To address the **AM SCD choice of manufacturing firms (RQB)**, this thesis focuses on the horizontal and vertical scope of SCs. The combination of both dimensions is ideally suited to capture the literature-based expectation of shorter, decentralized AM SCs (horizontal scope) with extensive outsourcing (vertical scope). Study B.1 approaches the vertical scope from the perspective of manufacturing firms as the most likely traditional SC actors that are confronted with AM make-or-buy decisions for their products. Basically, manufacturing firms must decide whether they commit resources to in-house AM or if they outsource the AM design and manufacturing process to AM service bureaus. Study B.1 investigates the rationales that are involved in the selected AM governance structures as the outcomes of AM make-or-buy decisions. By building a deep context-specific understanding for industrial AM, this study elaborates how the specific (emerging and digital) characteristics of AM technologies affect established arguments for the governance choice. Study B.2 takes the governance choice from a firm-centric (study B.1) to a network perspective. To account for the network perspective, study B.2 considers the viewpoints of all typical actors of AM SCs to explore the AM SCD choice and underlying rationales of focal manufacturing firms. Besides the vertical scope (in-house versus outsourcing), this study also targets the horizontal scope (central versus decentral) of AM SCDs and their interplay in order to reason on the literature-based vision of decentralized, outsourced AM SCDs. Both studies, B.1 and B.2, are embedded in the industrial AM context and, hence, target manufacturing firms from pioneering industries where industrial AM applications have started to create value (e.g., the aerospace and automotive industries). Their outlined characteristics are summarized in Table 1-2.

Table 1-2: Characterization of the studies B.1 and B.2.

| | Study B.1 | Study B.2 |
|---|---|---|
| **Focus** | Make-or-buy decisions (their outcome defines the vertical scope (governance structure) of AM SCs) | SCD decisions (decision for the horizontal scope (geographic dispersion) and the vertical scope (governance structure) of AM SCs) |
| **Addressed incumbents** | Manufacturing firms as the main actors that are confronted with AM make-or-buy decisions | Manufacturing firms as the focal firms that dominate the AM SCD choice |
| **Perspective of investigation** | Firm-centric perspective | Network perspective |
| **Purpose of investigation** | Elaboration of how arguments of established theories are modified in make-or-buy decisions in the industrial AM context | Exploration of cohesive SCD configurations for industrial AM and the involved rationales of manufacturing firms for selecting these configurations |
| **Temporality** | Past-/present-oriented | Past-/present-oriented |
| **AM context** | Industrial AM and industries where these applications create value (the aerospace, rail, automotive, and machinery and equipment industries) | Industrial AM and industries where these applications create value (the aerospace, rail, automotive, and machinery and equipment industries) |
| **Consideration of the AM context** | In-depth understanding of the industrial AM context from the perspective of AM-specific actors | Reflection on focal manufacturing firms from the perspectives of suppliers from the AM domain and industrial customers |

## 1.4 Research design and main contribution

After a brief characterization of the four studies, this section focuses on the understanding and use of theory and the methodological approaches chosen in this thesis. Overall, this thesis positions itself as theory-oriented research that also aims at supporting managers of manufacturing firms and LSPs in making informed decisions, as emphasized by the twofold research objective. To cover this range, this thesis makes use of different facets of **theory**. Generally speaking, the spectrum of theory is broad. In this thesis, it starts with the background literature that can act as an equivalent to theory and serves to define the study-specific research questions (e.g., to show the chasm between literature-based expectations and AM implementations from practice). On the other end of the spectrum, this thesis relies on grand theories that provide high-level theoretical perspectives and established relationships. For example, studies A.2 and B.2 follow a configurational approach, while study B.1 navigates within general relationships that are substantiated by transaction cost economics (TCE) and the resource-based view (RBV). The derived findings as the output of the four studies aim to contribute to theory development (e.g., theory building, theory elaboration, etc.) as is typical for theory-oriented research (Dul & Hak, 2008). However, when considering the relationships between theory and the conducted research in this thesis, it can be seen that there is overall more emphasis on the empirical context than on the applied grand theories. As summarized in Table 1-3, pure inductive research approaches, for which the collected empirical data are the driving force, or mixed inductive/deductive research approaches are applied in the studies A.1, A.2, and B.2. These studies aim at contributing to theory building based on findings that are directly drawn from the empirical context and then discussed in light of existing theory. Moreover, study B.1 makes use of an abductive approach and aims at elaborating existing theories instead of building new ones. This study develops a middle-range theory (MRT)[2] that provides a deep, context-specific understanding of the novel industrial AM context to bridge the gaps between empirical observations and grand theories.

In order to select suitable **methodologies** for the mostly inductive and abductive research approaches in this thesis, the character of the overarching and study-specific research questions was decisive: The research questions tackle the building of an understanding for the inner causal mechanisms involved in the development of AM business models and SCD choices. With that, they emphasize behavioral aspects in the research disciplines of business model research and OSCM research. This emphasis suggests viewing the involved research disciplines from the perspective of social science. In doing so, this thesis is aligned with the epistemological position of interpretivism, which supports the application of qualitative research methodologies (Mangan et al., 2004; Tashakkori & Teddlie, 1998). In this vein, the research presented in this thesis is dominated by qualitative research approaches (see Table 1-3), which are suitable for addressing the desired *how* and *why* questions (Eisenhardt, 1989). As summarized in Table 1-3, three of the four studies apply entirely qualitative research methodologies (studies A.2, B.1, and B.2). To be more specific, study A.2 follows the methodological practices of grounded theory as advocated by Corbin and Strauss (2015) and additional guidance provided by Gioia et al. (2013). The studies B.1 and B.2 both adopt multiple-case study approaches based on Yin (2014) and Eisenhardt's (1989) popular approach of within-case and cross-case analysis. Deviating from these qualitative research methodologies, study A.1 contains a mixed-methods approach of combining qualitative (taxonomy development) and quantitative (cluster analysis) methods (see Table 1-3).

Table 1-3: Overview of the research designs of the four studies.

| | **AM business model development** | | **AM SCD choice** | |
|---|---|---|---|---|
| | **Study A.1** | **Study A.2** | **Study B.1** | **Study B.2** |
| **Relationship between theory and research** | Combination of inductive and deductive | Inductive | Abductive | Inductive |
| **Theoretical purpose** | Theory building | Theory building | Theory elaboration | Theory building |
| **Approach** | Mixed-methods research | Qualitative research | Qualitative research | Qualitative research |
| **Methodology** | Taxonomy development (qualitative) and cluster analysis (quantitative) | Grounded theory | Case study research | Case study research |

Based on the outlined use of theory and applied methodological approaches, this thesis contributes to theory development in the OSCM and business model literature on AM in four main ways:

First, this thesis provides in-depth empirical insights into AM business model and SCD choices. By relying on collected real-world perspectives, this thesis makes it possible to analyze the **rationales** behind the AM-driven business model development of LSPs and SCD decisions of manufacturing firms to enhance the understanding of the decision outcomes. Such inner causal mechanisms have

[2] MRT is used in this thesis for both the process termed "middle-range theorizing" (Stank et al., 2017) and the resulting theory termed "middle-range theory" (Craighead et al., 2016), since both abbreviations are used in the literature.

so far not been sufficiently addressed in previous research and extend the growing body of knowledge on AM SCDs (e.g., Durach et al., 2017b; Tziantopoulos et al., 2019; Verboeket & Krikke, 2019) and business models (e.g., Bogers et al., 2016; Holzmann et al., 2020a; Holzmann et al., 2020b). On this basis, the insights gained can serve as a reference point for the development of quantitative decision-support models for AM.

Second, this thesis enriches the current state of the literature with **context-specific** knowledge. Apart from study A.1, this thesis concentrates on industrial AM, in particular, on metal and high-quality polymer applications and on pioneering industries for such applications. Overall, this is a challenging industry context with high quality requirements, reflected in the need for testing procedures, established standards, and extensive certification processes. Consequently, the collected data and derived findings are context-specific, which is a direct response to the call for more investigations of AM within specific application domains (Ford & Despeisse, 2016; Hohn & Durach, 2021; Rehnberg & Ponte, 2018) to reduce the discrepancy between theoretical expectations and implementations from practice.

Third, by exploring how incumbents currently react to AM and how the technologies infuse their strategic decisions, this thesis takes a **process-based** perspective. Specifically, the combination of the two AM business model studies A.1 and A.2 provides both a comprehensive overview of current reactions to AM and resulting business model dynamics as well as a grounded view on “finished” AM business models. By considering the “small steps” and current dynamics, this thesis explores the interactions of AM with traditional business models and the integration of AM into existing SC structures. For example, it shows how AM SCDs are constrained by existing processes, firm characteristics, and industry traditions. This thesis thereby contributes to the scarce literature focusing on how AM business models and SCDs evolve (e.g., Rong et al., 2018) rather than on solely future-oriented visions.

Fourth, AM stands in this thesis for a set of **inherently digital and emerging technologies**. By separating these characteristics, this thesis elaborates how AM modifies established arguments of grand theories for make-or-buy decisions (study B.1). Moreover, AM is at several points throughout this thesis contrasted with mature (instead of emerging) and “analog” (instead of direct digital) manufacturing technologies. This separation of the specific characteristics of AM facilitates drawing comparisons with similar digitalized technologies or industries (e.g., the semiconductor industry) or with innovations that share the emerging characteristics. Thereby, this thesis contributes to building broader knowledge of how incumbents like manufacturing firms and LSPs are trying to stay competitive in the upcoming era of digitally dominated business models and SCs (Goldsby & Zinn, 2016; Stank et al., 2019).

Overall, it is noteworthy that the in-depth, real-world perspectives in this thesis are at multiple times able to provide a more differentiated view than the existing OSCM and business model literature. With that, more nuanced reactions to AM and ways of integrating AM into existing or new business models are derived. Similarly, this thesis identifies valid reasons for value-creating SCDs that differ from the envisioned decentralization and extensive outsourcing. These SCDs fit firms’ competitive strategies at their current stage of AM implementation and foster the discussion of which AM SCDs will survive once AM matures. The more differentiated views outlined here also set the ground for deriving managerial implications in this thesis: The studies raise awareness among manufacturing firms of alternative paths to suitably integrate AM into their SCs, focusing on the spectrum of geographic dispersion and governance structure. In addition, support is offered for managers of LSPs that are in the process of getting involved with AM and designing AM business models.

## 1.5 Thesis structure

The first chapter of this thesis has provided reasons why the revolutionary characteristics of AM can bring major changes to incumbents' operations, SC structures, and business models. It has further briefly sketched the current state of the literature and derived research gaps in the OSCM and AM business model literature that are tackled in this thesis. On this basis, this chapter has developed the research objective and two overarching research questions. Moreover, it has shown how the overarching research questions are addressed by providing a glimpse of the content and research design of the four studies and by summarizing their main contribution. Indeed, it is also the two overarching research questions that guide the further structure of this thesis. As two main building blocks, they divide the main body of this thesis into two parts, part A for addressing RQA and part B for addressing RQB. Figure 1-3 provides an overview of the overall structure of this thesis.

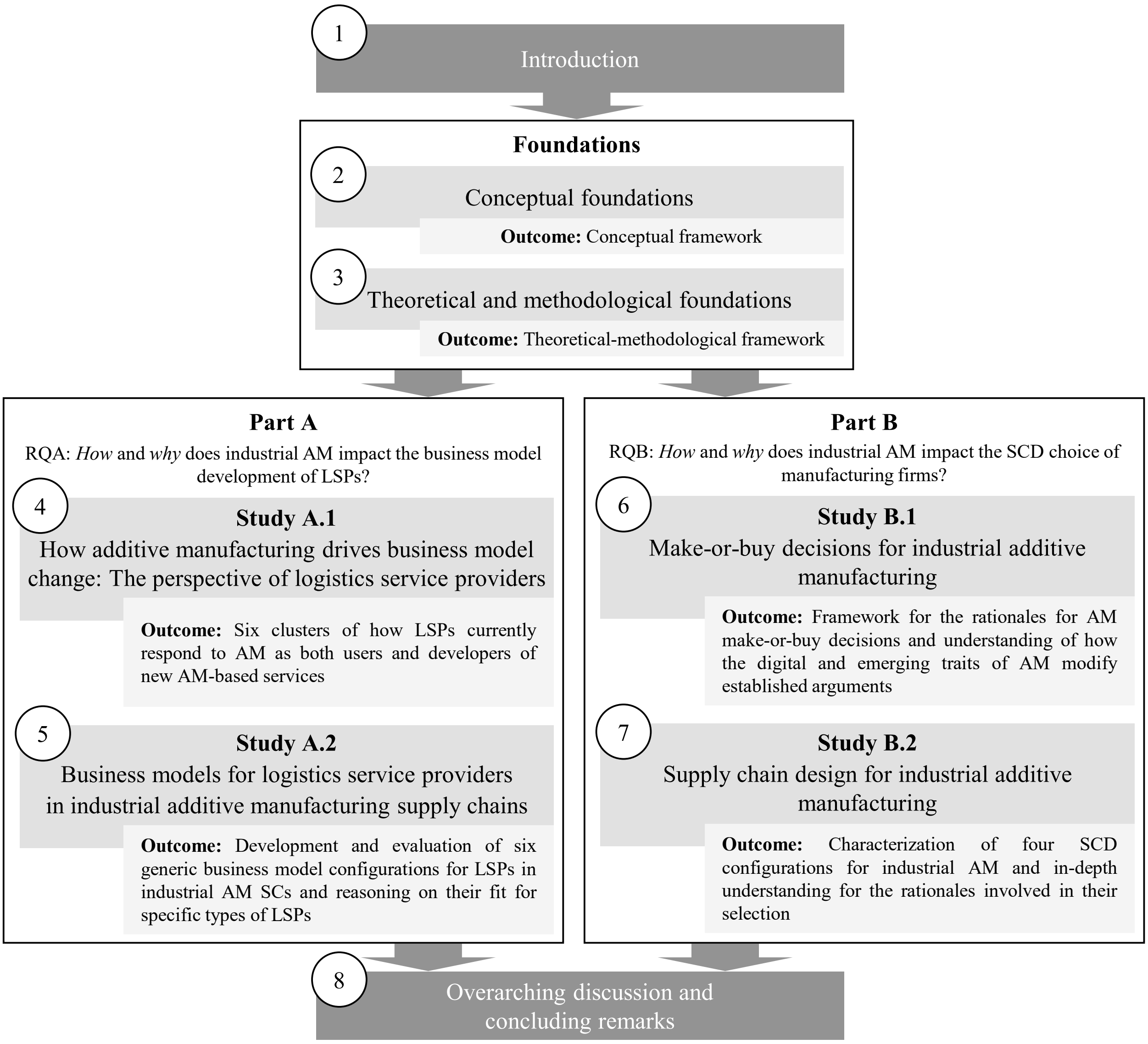



Figure 1-3: Overview of the structure of this thesis.

After this introduction, **Chapter 2 and Chapter 3** develop the conceptual and theoretical-methodological foundations of this thesis. They deepen the motivation for the overarching research questions and frame the four studies. To be more concrete, Chapter 2 builds a literature-based understanding of the industrial AM context and the expected impact of AM on the business model development of LSPs and the SCD choice of manufacturing firms. Furthermore, a comprehensive overview of previous research from the OSCM and AM business model communities is provided. In sum, Chapter 2 leads to a conceptual framework for this thesis. As an equivalent, Chapter 3 is dedicated to the theoretical and methodological foundations of this thesis. It first establishes an understanding of theory, which sets the ground for explaining the applied theoretical lenses for the four studies. In addition, the relationships between theory and the conducted research are evaluated in detail. The second part of Chapter 3 then focuses on the methodological guidance, in particular, on qualitative research methodologies and their application in this thesis. Chapter 3 concludes by deriving a theoretical-methodological framework.

The main body of this thesis consists of the four independent studies. Part A includes **Chapter 4 and Chapter 5**, which are composed of the studies A.1 and A.2, correspondingly. Hence, part A focuses on the AM business model development of LSPs. Figure 1-3 briefly summarizes the outcome of the studies to address RQA, including distinct profiles of LSPs' current reactions to AM (study A.1) and a reflective view on potentially "finished" configurations of AM business models for LSPs (study A.2). In the same manner, part B is divided into **Chapter 6 and Chapter 7**, which comprise the studies B.1 and B.2 to contribute to RQB. As illustrated in Figure 1-3, this is done by building a nuanced understanding of manufacturing firms' make-or-buy decisions for industrial AM in light of existing theories (study B.1) and by exploring AM SCD configurations and their underlying rationales (study B.2).

This thesis ends with **Chapter 8**, which foremostly discusses the results of this thesis with respect to the overarching research questions. Furthermore, it delineates the contribution to theory and practice, addresses overarching limitations, and suggests broader directions for future research.

## 2 Conceptual foundations

The introduction has referred to various examples of AM and its expected revolutionary effects to motivate the overarching research questions. This chapter aims to deepen the motivation for these overarching research questions. For this purpose, it provides the necessary conceptual foundations and a comprehensive overview of the relevant literature background.

To frame this chapter, the **CIMO-logic** from design science is adopted. It is suitable for this thesis since design science aims at solving real-world business problems in their context and is attested to have the potential to bridge practice and theory (Holmström et al., 2009). Additionally, it is suitable for early-stage research, such as in the emerging industrial AM context, since it targets both problems and possible solutions (Holmström & Partanen, 2014). The CIMO-logic, as developed by Denyer et al. (2008), proposes that mechanisms produce a specific outcome. With that, it differs from a simple input-output (IO)-logic. It follows the logic of prescription by describing how within a specific *context* (*C*), an *intervention* (*I*) triggers a *mechanism* (*M*) to lead to a specific *outcome* (*O*) (Denyer et al., 2008). The context describes the external or internal environment in which the intervention is embedded. Here, it refers to industrial AM as emerging digital technologies that establish a novel technological context. The intervention refers to the expected power of AM to invoke the (re-)design of established business models and SCs. Incumbents like manufacturing firms and LSPs are equipped with their traditional resources that are manifested in their traditional business models and SC structures. AM is expected to trigger a mechanism of (re-)designing business models and SC structures. The outcomes of the AM-based interventions are business models and SCDs that leverage the specifics of AM and ideally enable incumbents to gain a sustained competitive advantage in the industrial AM context. Figure 2-1 illustrates the CIMO-logic for both overarching research questions. In addition, it serves as an agenda for the sections in Chapter 2 and demonstrates the starting points of the four studies.

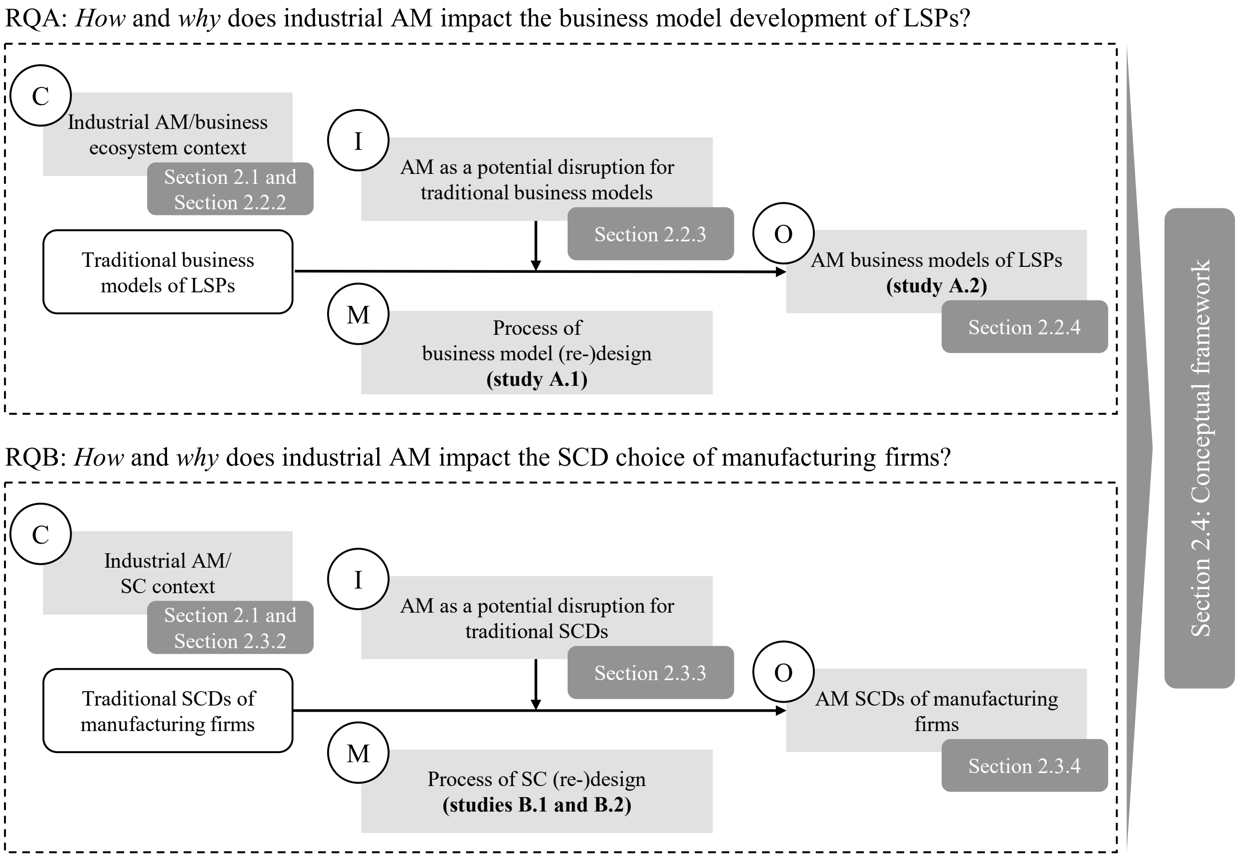



Figure 2-1: CIMO-logic for the two overarching research questions.

With reference to Figure 2-1, Chapter 2 is structured as follows: Section 2.1 introduces and characterizes the industrial AM context by providing insights into state-of-the-art AM technologies and their operational implications. Section 2.2 builds an understanding of why AM – as an intervention – challenges incumbents, in particular LSPs, to rethink their traditional business models. Analogously, Section 2.3 establishes why AM challenges incumbents, in particular manufacturing firms, in their traditional SCD choice. Finally, in Section 2.4, a conceptual framework is derived, which draws on the CIMO-logic to motivate and detail the overarching research questions that frame the four studies presented as the main body of this thesis.

## 2.1 Additive manufacturing as emerging digital manufacturing technologies

This section introduces industrial AM technologies and their operational consequences by providing insights into their unique features and fields of application in industry. Starting with an overview of the state of AM technologies in Section 2.1.1, a brief description of the AM process is given from a technological and economic perspective in Section 2.1.2. Advantages and challenges associated with AM technologies are summarized in Section 2.1.3. Lastly, in Section 2.1.4, suitable fields of application for AM are outlined.

### 2.1.1 Overview of the state of the art

AM is defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM, 2021, p. 1). This definition contains two essential characteristics of AM. First, the AM process is based on the *digital* product specification ("the 3D model data"), which is commonly provided as a computer-aided design (CAD) model. Second, the material is *additively* applied in layers, which ultimately leads to the creation of a 3D object. Both aspects underline why AM contrasts with traditional manufacturing technologies.

**Digital:** The digital input of the AM process defines how the product is manufactured straight from the digital product specification. This is a direct, one-step process without the need for manually "translating" the product specifications to the specifics of the machine. Product-specific tooling and setup are not required for the AM process, and this characteristic of AM is enabled by the inherent flexibility of AM machines to manufacture different designs. For this reason, AM machines are also defined as general-purpose equipment, and AM as a direct digital manufacturing process that ideally does not require further equipment (Holmström et al., 2016). These inherently digital characteristics set AM apart from specific traditional manufacturing technologies, which require manual intervention (e.g., tooling and setup) and multiple manufacturing steps potentially carried out with multiple machines (Gibson et al., 2015; Verboeket & Krikke, 2019; Weller et al., 2015).

**Additive:** The additive process significantly differs from traditional manufacturing technologies like turning and milling, where an object is subtractively carved out of a block. In addition, it contrasts with formative manufacturing technologies that use tools like molds and casts to form a part (Ngo et al., 2018). Parts are manufactured in a layer-by-layer fashion, and each layer is a cross-section of the part derived from the CAD model (Gibson et al., 2015).

Since the 1980s, the development of AM technologies has progressed rapidly. The patent of Charles Hull's developed Stereolithography as the first AM process was granted in 1986 and was followed by several other patents, including Fused Deposition Modeling in 1992 (Beltagui et al., 2020; Huang et al., 2013). The first AM machines became operational in the early 1990s. Starting as niche technologies, they were initially used mainly for military applications. The overall development of the technologies, from their introduction in the 1980s to the present stage, can be divided into four phases that gradually extended the range of opportunities for AM implementation (Rayna

& Striukova, 2016b). This development process of AM is illustrated in Figure 2-2 and described in the following paragraphs.

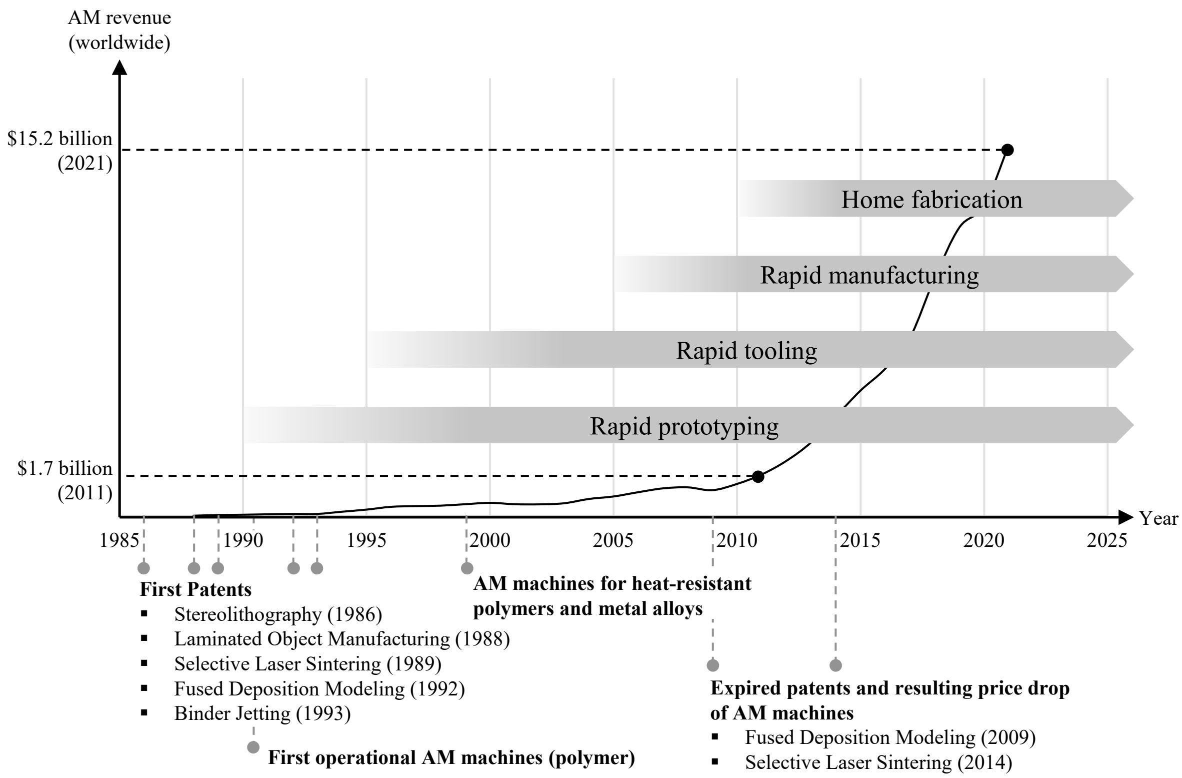



Figure 2-2: Development of industrial AM (growth curve based on Wohlers Associates (2021b)).

In the early 1990s, AM was limited to polymer applications. The novel technologies were mainly used by large firms to produce polymer prototypes, termed **rapid prototyping**. Initial obstacles of AM, including low quality, slow processes, high costs, and restriction to small objects, were not problematic for such applications. Instead, these disadvantages of early AM were outweighed by the faster availability of additively manufactured prototypes compared to traditionally manufactured ones and, thus, by reduced development times for new products (ISO/ASTM, 2021; Weller et al., 2015). The automotive industry is coined as one of the earliest and most fruitful users of AM for prototyping. Among others, applications include design validations and fit and function testing (Wohlers Associates, 2021b).

With the emergence of AM technologies for heat-resistant polymers and metal alloys, the second phase of AM began in the late 1990s. Using **rapid tooling**, tools, molds, and jigs and fixtures can be produced faster and often cheaper than with traditional manufacturing technologies (Rayna & Striukova, 2016b). Moreover, AM enables firms to flexibly react to design improvements and error corrections, which is otherwise hindered by the time-consuming and expensive traditional manufacturing of tools (Hiemenz, 2013). For instance, it is possible to additively manufacture metal mold inserts that facilitate the integration of conformal cooling channels. As a result, the additive process enables faster molding cycle times, and the functional improvements extend the lifespan of these tools (Wohlers Associates, 2021b).

It was not until key patents for two AM processes, Fused Deposition Modeling and Selective Laser Sintering, expired in 2009 and 2014 that AM became more accessible for SMEs and private households, which strengthened the development of the consumer side of AM technologies. With the increasing availability of inexpensive and fully assembled AM machines, internal research and development activities of firms increased and fostered the identification of new fields of application for AM, and this, again, amplified technological advancements (Wohlers Associates, 2021a). Thus, new AM technologies and materials were developed, and prices continued to drop while the quality of AM parts and the process accuracy improved (Gibson et al., 2015). In the late 2000s, the technological development had reached a stage enabling the application of AM for **rapid manufacturing**, the direct digital manufacturing process of final products straight from a digital file, ideally without additional machining (Rayna & Striukova, 2016b). The aerospace and the medical industries are recognized as the early pioneers of additively manufacturing parts for their final use (Holmström et al., 2010). Starting from these industries, AM applications have developed in various industries, including transportation and logistics, construction and landscaping, and consumer-oriented industries (e.g., the toy industry) (EY, 2019; Gebhardt et al., 2019). Hence, the range of end products that can be additively manufactured is constantly growing.

From a consumer perspective, Rayna and Striukova (2016b) expect the so-called **home fabrication** to be the fourth and final phase of the technological development of AM that began in the early 2010s. Driven by the development of low-cost personal "desktop" 3D printers for polymer applications, end users started to "print" objects themselves. The years 2013/2014 marked the peak of the consumer 3D printing hype (Gartner, 2014). However, home fabrication has since then progressed slowly, and its large-scale spread remains questionable for now. Current barriers that firms and end users face on the development path toward technological maturity may open the door for intermediate implementation forms of AM, for example, **local fabrication**. This form denotes firms and end users that rely on nearby AM-specific service providers, like AM service bureaus, for manufacturing services and other AM-related services (Rayna & Striukova, 2016b).

All four phases (i.e., rapid prototyping, rapid tooling, rapid manufacturing, and home fabrication) are currently underway. As a result, various terms are used to describe AM technologies, their purpose, and their benefits for specific types of applications.[3] In particular, in the non-technical context and in the media, 3D printing has oftentimes been used as a synonym for AM. However, in recent years, 3D printing has increasingly been associated with low-end machines in terms of their price, capacity, and manufacturing quality. Such machines are typically used in the consumer context (ISO/ASTM, 2021; Thomas-Seale et al., 2018). Building on this differentiation, this thesis is concerned with the use of the technologies for industrial production, termed industrial AM. It follows Gibson et al. (2015) by using AM as a generic term for the variety of manufacturing processes that add materials in layers. Up-to-date industrial applications for AM include prototypes, tools (e.g., patterns, cores, molds, jigs, fixtures, assembly aids, etc.), and parts for final use. These final parts are sold as new parts or spare parts to industrial customers. Furthermore, firms use AM internally for research and development activities and for educational purposes (Gartner, 2019). According to Wohlers Associates (2021b), end-use parts (31.5%), prototypes (25.2%), and research and education (11.6%) currently account for the largest share of AM applications in industries. These shares show that industrial AM has evolved from its historical applications for prototypes; firms are increasingly using the technologies for serial applications (Sertoglu, 2022).

As demonstrated in the timeline in Figure 2-2, the increase in AM applications and the growth of the AM market since the 1980s are closely linked to technological advances in AM machines and materials. Various AM technologies have evolved, and they are at different stages of their individual paths toward maturity (Featherston et al., 2016). This thesis understands the sum of industrial AM technologies to be currently in an **emerging stage**, analog to Ghobadian et al. (2020) and Rong et al. (2018). In such a stage, technologies remain under development as their technical characteristics are not yet fully established (Cavalcante, 2013). This results in high technological uncertainty and complexity. In this vein, Day et al. (2000, p. 5) term the "exploratory usage patterns" of customers, the "scant market knowledge," and "embryonic competitive structure" as the

[3] Historically, 3D printing and other terms, for example, (additive) layer manufacturing, additive processes, additive techniques, additive fabrication, and (solid) freeform fabrication, have been used as common synonyms for AM (ISO/ASTM, 2021).

"most confusing aspects of emerging technologies." These aspects are also taken up in the definition of Hung and Chu (2006, p. 104), who state that emerging technologies are core technologies but have not yet "demonstrated potential for changing the basis of competition." Facing high technological uncertainty and complexity, firms' decisions for emerging technologies are rather driven by the promises that these technologies hold for their mature stage than by their current performance (Adner & Levinthal, 2002). Finally, it is noteworthy that the emerging stage usually characterizes a period and, thus, a longer process that has a pre-history of technical development and involves the evolution of a technology within a given domain of application and/or the transfer to a new domain (Adner & Levinthal, 2002).[4]

Currently, industrial AM is increasingly approaching a stage of becoming an early mainstream market, as indicated in Gartner's (2019) proposed "Hype Cycle for Imaging and Print Services." Gartner (2019) locates "enterprise 3D printing" (as an equivalent to industrial AM) at the "Slope of Enlightenment" and about to enter the "Plateau of Productivity" in the hype cycle. The growth potential of the worldwide AM market continues to be high, as demonstrated by the recent ten-year market growth rate of 25.7% (2011–2020) and visualized in Figure 2-2 (Wohlers Associates, 2021b).[5] The literature commonly terms such highly dynamic markets as **nascent markets** (Rask & Günzel-Jensen, 2019), and this thesis also uses this term. High velocity and unpredictability are attributes of nascent markets (Eisenhardt, 1989). Moreover, Santos and Eisenhardt (2009, p. 644) summarize, "nascent markets constitute unstructured settings with extreme ambiguity" to highlight that such markets lack established patterns and logics that guide the actions and structure an industry. For instance, firms are not fully aware of the positions and specific competencies of their suppliers, customers, and other partners in nascent markets. Furthermore, it is not fully established which competencies are strategically valuable and how they can contribute to a competitive advantage (Eisenhardt & Bingham, 2017). Aldrich and Fiol (1994, p. 645) raise awareness for additional challenges that firms face in the so-called first "formative years" of nascent markets. Among them are the recruitment of untrained employees and skepticism from stakeholders.

This section has defined AM technologies and established an understanding of their historical development and current stage as emerging technologies that evolve in a nascent market. Even though this thesis abstracts from specific industrial AM technologies and market settings, it still needs a clear perspective on the consequences of these technologies for firms in order to investigate how their business model development and SCD choice are impacted. Thus, the following section will provide an overview of AM technologies, outline the process of additively manufacturing a part, and raise awareness for the main technological and economic implications.

### 2.1.2 Technological and economic perspectives

At the current emerging stage, there is a great variety in state-of-the-art AM technologies. For example, the AM consulting firm AMPOWER identified more than 18 different types of metal and more than 16 different types of polymer AM processes with various sub-technologies in 2020/2021 (AMPOWER, 2020, 2021a). This **variety in technologies** results in several hundred different types of machines that are currently available on the market (Gebhardt et al., 2019). For a condensed overview, the ISO/ASTM 52900 standard provides a classification of seven main AM processes (ISO/ASTM, 2021). Each of the seven AM processes serves as an umbrella term that groups several AM technologies which fall into this category based on their similar characteristics. Table 2-1 provides an overview of the seven process categories, exemplary AM technologies, and suitable materials.

[4] Technologies may also permanently remain in an emerging stage when the commercialization of technologies fails several times. For example, Rask and Günzel-Jensen (2019) term the development of the technology of electric vehicles as a 100-year-plus phenomena and, thus, as a permanently emerging technology.

[5] Market growth was slowed down in 2020 to 7.5% due to the COVID-19 pandemic, but the recently published market growth rate of 19.5% for 2021 suggests that the AM industry is recovering well (Sertoglu, 2022).

Table 2-1: Classification of AM processes and associated technologies and materials (based on ISO/ASTM (2021), Wohlers Associates (2021b), and Calignano et al. (2017)).

| AM process | Characterization (ISO/ASTM, 2021, p. 2–3) | Exemplary AM technologies | Materials |
|---|---|---|---|
| Material Extrusion | "material is selectively dispersed through a nozzle or orifice" | Fused Deposition Modeling | Polymer |
| Vat Photopolymerization | "liquid photopolymer in a vat is selectively cured by light-activated polymerization" | Stereolithography, Digital Light Processing | Polymer, ceramic |
| Powder Bed Fusion | "thermal energy selectively fuses regions of a powder bed" | Selective Laser Sintering, Selective Laser Melting, Electron Beam Melting | Metal, polymer, ceramic |
| Binder Jetting | "liquid bonding agent is selectively deposited to join powder materials" | 3D Printing, Ink-Jetting, S-Print, M-Print | Metal, polymer, ceramic, sand |
| Material Jetting | "droplets of feedstock material are selectively deposited" | PolyJet, Ink-Jetting, ThermoJet | Polymer, wax |
| Direct Energy Deposition | "focused thermal energy is used to fuse materials by melting as they are being deposited" | Direct Metal Deposition, Laser Deposition, Laser Consolidation, Electron Beam Direct Melting, Wire Arc Additive Manufacturing | Metal (powder and wire) |
| Sheet Lamination | "sheets of material are bonded to form a part" | Ultrasonic Consolidation, Laminated Object Manufacture | Metal, polymer, paper |

Until today, Powder Bed Fusion and Direct Energy Deposition are the most commercially available and relevant AM processes for metal applications (AMPOWER, 2020; Thomas-Seale et al., 2018). Well-known and vastly applied AM processes for polymer parts are Material Extrusion and Vat Photopolymerization (Gibson et al., 2015; Sculpteo, 2021). Generally speaking, the AM processes structured in Table 2-1 differ in the way materials are added layer upon layer. Furthermore, they differ in their newness and origin in traditional manufacturing technologies. For example, Direct Energy Deposition includes technologies like Wire Arc Additive Manufacturing that directly adopt traditional arc welding tools and wire as raw material and, thus, are closely related to this traditional manufacturing technology (Ding et al., 2015). As further exemplified in Table 2-1, the AM processes are suitable for specific types of materials that are typically used in the form of powders, wires, filaments, liquids, or sheets. The most common materials used in AM are polymers, followed by metals and alloys (Wohlers Associates, 2021b). Ceramics are relevant for medical applications (e.g., reconstruction of teeth), and concrete has gained increasing attention for contour crafting, a process that extrudes concrete through big nozzles with high pressure for the construction industry (Ngo et al., 2018). AM of biomaterial (i.e., living cells) is highly researched and could be a significant advancement in the repair and replacement of organs (Schubert et al., 2014). Moreover, wood particles, sand, wax, food, and several other materials can be used for specific AM technologies (Rayna & Striukova, 2016b; Wohlers Associates, 2021b).

While it has been demonstrated that the broad spectrum of AM technologies differs greatly in the way the material is added in a layer-by-layer fashion, the technologies all share the same **four-step process chain**. The design phase is followed by pre-processing, the actual manufacturing process, and necessary post-processing steps (Eyers & Potter, 2015), as illustrated in Figure 2-3. For this thesis, an overall distinction is made between the digitally dominated design process and the AM process that transforms the digital file into a physical object in an ideally one-step process (see Figure 2-3).

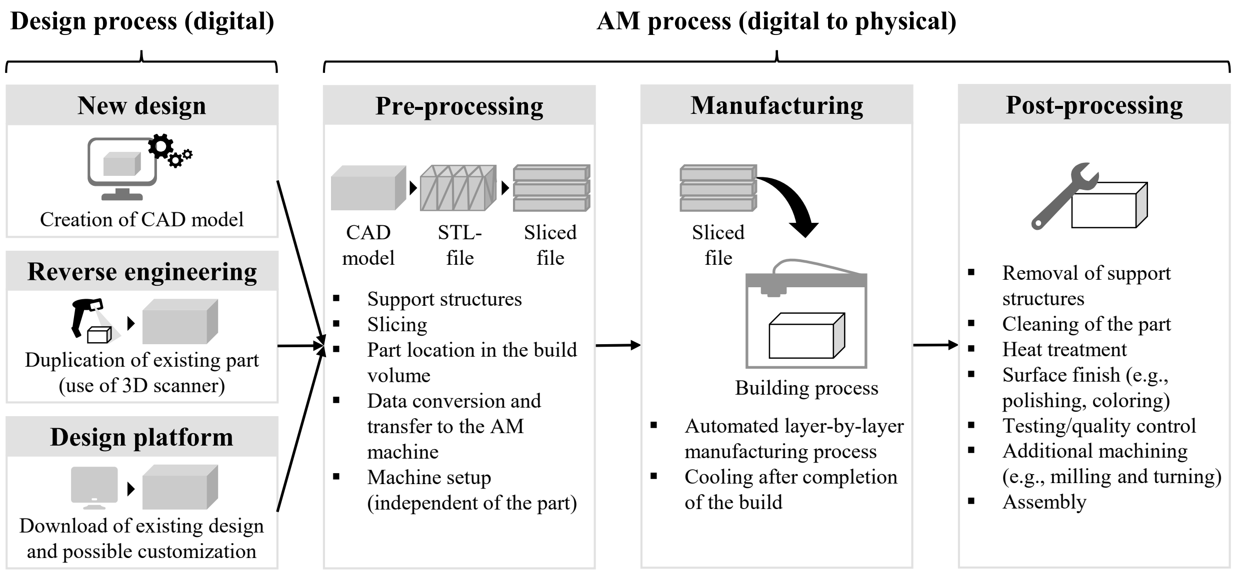



Figure 2-3: The AM process chain.

The **design phase** marks the starting point of the development of an AM part. It serves to create the 3D computer model of the to-be-manufactured object and, hence, provides the necessary digital input for the manufacturing process. Basically, there are three ways to create a digital model, as differentiated by Rogers et al. (2016) and illustrated in Figure 2-3. A new design model can be constructed using CAD software or it can be generated by reverse engineering (Eyers & Potter, 2015).[6] The procedure of reverse engineering is particularly advantageous for very complex geometries and obsolete spare parts where the original documentation may have gotten lost or never existed (Raja & Fernandes, 2008). As a third option, it is also possible to use existing CAD models by purchasing and downloading them from AM design platforms (Rogers et al., 2016). Such platforms foremostly exist for end consumers (Hudson et al., 2016; Rayna et al., 2015), as will be detailed in Section 2.2.2.

The **pre-processing phase** includes the conversion of the CAD model into a suitable file format. STL-format (Surface Tessellation Language or Standard Triangle Language) is the de facto industry standard for AM (Gibson et al., 2015). The STL-format describes the surface geometry as a tessellation of triangles and is the basis for calculating the slicing of the object into 2D layers (ISO/ASTM, 2021). Specific computer-aided manufacturing (CAM) software is used to prepare the STL-file for the manufacturing process by converting it into a “legible” file format and generating process parameters for the AM machine (Sturm et al., 2017). Slicing is the essential CAM process. It generates slice data, and each slice specifies a 2D cross-section of the object that represents a to-be-manufactured layer (Gibson et al., 2015). Note that support structures may be required to counter thermal residual stresses and mechanical stresses in the manufacturing process. They must be added to the object’s design before the slicing process. In addition, whenever multiple parts are manufactured in one build to improve capacity utilization, their particular location and orientation must be defined within the build volume (Zhang et al., 2019).[7] The sliced file is then transferred to the AM machine, which commonly needs to be set up before the start of the build (Baumers & Holweg, 2019; Li et al., 2017a). The necessary steps are ideally independent of the to-be-manufactured part and include preparations like material loading, machine initialization,

[6] Reverse engineering describes the process of obtaining a CAD model by digitizing an existing object with a 3D scanner. Thus, an existing part can be duplicated and further modified without any available drawings and documentation of the CAD model (Raja & Fernandes, 2008).

[7] The build volume, also termed build envelope, defines the enclosed location within AM machines constraining the size within which parts can be manufactured (ISO/ASTM, 2021).

process parameter setup, and pre-heating. In the case of necessary material changeover, cleaning may be an additional time-intensive step (Zhang et al., 2019).

Once the digital file is transferred to the AM machine and the system is set up, the **manufacturing phase** describes the automated manufacturing process with minimum involvement of manual labor (Gibson et al., 2015). Materials are applied layer-wise, and this process may take from a few minutes or hours up to multiple days in larger AM machines (Eyers & Potter, 2015). The overall manufacturing time depends on the product size, the required precision, and the composition of the different parts in one build. After the manufacturing process is completed, some AM technologies require additional cooling time (Li et al., 2017a; Zhang et al., 2019).

In order to achieve the desired properties of the final product, a **post-processing phase** is oftentimes necessary. It includes the removal of support structures, cleaning of the part, heat and surface treatments, and quality assessment (Zhang et al., 2019). Additional steps may involve polishing, coloring, and also machining and assembly (Eyers & Potter, 2015). Some AM technologies require subsequent traditional manufacturing steps. For instance, AM technologies like Wire Arc Additive Manufacturing produce large near-net-shape AM parts in a fast manner. Traditional subtractive machining, for example, milling or turning, is required to remove material until the final shape is reached (Williams et al., 2016).

From a **technological perspective**, the described four-step AM process chain is influenced by the constraints of a specific AM technology and the respective commercially available machines. Worth noting is that AM machines differ in their size, speed, use of multiple materials, accuracy, surface quality, and the intensity of necessary post-processing steps. For instance, AM machines that rely on a powder bed self-limit the size of applications to the machines' build volume (Baumers & Holweg, 2019). Other AM processes like Direct Energy Deposition are based on free-standing robots to fuse the metal powder or wire. Hence, there is no machine build volume consideration in such technologies and consequently no size limitations for applications. It is further noteworthy that pre- and post-processing currently appear to be inevitable for industrial AM applications, particularly for metal AM (Knofius et al., 2021). AM processes like Direct Energy Deposition and metal Laser Powder Bed Fusion are complex to handle and require extensive post-processing. In contrast, operational requirements and the need for pre- and post-processing are reduced and partly automated for polymer AM, especially for non-functional parts like prototypes, tools, or jigs and fixtures (Mellor et al., 2014; Nelaturi et al., 2019).

Finally, from an **economic perspective**, the four-step AM process differs in the required investment and operational costs. "Desktop" polymer 3D printers are commonly associated with selling prices below $5,000, whereas industrial AM machines require a significant investment, on average, around $54,000 for polymer and $500,000 for metal AM machines in 2020 (Wohlers Associates, 2021b). Additionally, the structure of operational costs for the AM process significantly differs from traditional subtractive manufacturing. Without the need for tooling and product-specific setup, fixed production costs are relatively low. Overall, they consist of build costs and post-processing costs, which differ for specific AM technologies. For instance, the build costs directly reflect the required materials for an AM technology (material costs), the fixed setup costs (e.g., for cleaning and pre-heating), and indirect costs associated with a specific AM technology (e.g., for energy consumption, material consumption, maintenance, and overheads during the build time) (Baumers et al., 2017). Based on this technological dive into the AM process chain, the next section provides an overview of the key advantages and challenges of AM technologies at their current emerging stage.

## 2.1.3 Advantages and challenges

The following summarizes the operational advantages and challenges of AM, and Table 2-2 provides a conclusive summary. A central advantage of AM compared to traditional manufacturing technologies is the **freedom of design**. Engineers are not constrained by manufacturing restrictions in the creation of unique and complex geometries. AM enables the integration of such complex geometries in a single manufacturing step, which would not be possible using traditional manufacturing technologies (Durach et al., 2017b). Closely related is the opportunity for functional integration and process integration provided by AM. Due to the reduced manufacturing restrictions of the AM process and the high degree of freedom in design, engineers can realize multiple functions in just one component rather than in multiple components. Combining multiple features in a single part reduces the assembly time. Thus, multiple production steps, which would traditionally be performed one after the other and, if necessary, on different machines, may be combined in one (Chua & Leong, 2017).

Moreover, the potentially more complex and functionally integrated components can be produced without correlating higher costs in AM (**"complexity for free"**) (Chua & Leong, 2017; Hopkinson & Dickens, 2003). Thus, unlike traditional manufacturing, product complexity has no direct effect on the manufacturing costs and production time (Hopkinson & Dickens, 2003; Oettmeier & Hofmann, 2017). An essential aspect in this regard is the high automation of AM. The actual manufacturing process requires little manual labor input, reducing the relevance of labor costs in the AM production costs (Chan et al., 2018). The remaining manual pre- and post-processing steps are expected to become increasingly automated in the future (Khajavi et al., 2014). Furthermore, employees are expected to require no or limited specific know-how for the process of additively manufacturing a part (Chekurov et al., 2018).

Another advantage of AM lies in the **general-purpose** characteristics of **AM machines**. Whereas traditional manufacturing often requires highly specific machines for individual production steps, AM machines are inherently flexible to manufacture different designs (Hedenstierna et al., 2019). Different designs can even be manufactured in one build and, hence, in a parallel manufacturing process (Atzeni & Salmi, 2012). The flexibility of AM machines further eliminates the need for a time-consuming setup and the expensive production of tools and molds. This significantly reduces fixed production costs, ramp-up time, and shortens the time to market (Ben-Ner & Siemsen, 2017; Holmström et al., 2010). To modify AM parts, only the CAD file and not the AM machine and/or specific tools need to be changed (Huang et al., 2013), which accelerates the process of product development. An additional consequence of the general-purpose characteristics is that the production becomes geographically independent of manufacturing locations for tools and molds (Verboeket & Krikke, 2019). With that, the general-purpose AM machine can be viewed as a "compact" production unit that is highly independent. AM processes with low pre- and post-processing requirements entail that the technologies have low space requirements and become transportable, for example, in the form of mobile AM micro-factories (Rauch et al., 2015).

Furthermore, AM has the potential to increase **resource efficiency** compared to traditional manufacturing technologies. Material waste can be reduced based on the additive instead of the subtractive process. The additive process only applies material that is required for the part, contrasting subtractive manufacturing from a block. This aspect is indicated by a better (closer to 1:1) "buy-to-fly" ratio of AM, which puts the weight of the raw material in relation to the weight of the final manufactured product (Gibson et al., 2015). Excess material, for example, powder for Powder Bed Fusion, can be recycled to a certain degree. For instance, Ford and Despeisse (2016) estimate the recyclability of unused metal powder at 95% to 98%. Besides, AM design optimizations open up the possibility of manufacturing products with new features and an extended life span. For instance, lightweight components for aircraft and cars may lead to a reduction in fuel consumption and, thus, $CO_2$ savings. Moreover, positive environmental effects may be realized with more stable or resistant components and additional functions like cooling channels in closed components (Thomas, 2016).

The described advantages are partly outweighed by challenges related to AM that limit the range of applications suitable for the technologies. **High costs** associated with AM compared to traditional manufacturing are one challenge at the current emerging stage. For example, the advantages of more complex, fewer, and functionally integrated AM parts oftentimes lead to higher costs. Moreover, consolidated AM parts entail a loss of flexibility, for instance, in the case of failure. As a result, consolidated AM parts more probably need to be replaced entirely, whereas traditionally manufactured parts facilitate the repairing and replacing of sub-components (Knofius et al., 2019). In addition, commonly listed are the high costs for raw materials, the investment in AM machines, and the high manufacturing costs, including energy costs (Berman, 2012; Durach et al., 2017b; Sasson & Johnson, 2016). The cost disadvantage of AM compared to traditional manufacturing technologies becomes a factor for large volumes. There is a lack of economies of scale associated with AM based on the lack of fixed costs for tooling and setup. On this basis, previous studies have assumed constant unit costs, independently from the production volume (e.g., Hopkinson & Dickens, 2003). However, it is noteworthy that manufacturing costs for AM depend on the capacity utilization of the build volume of AM machines (Ruffo et al., 2006) and the composition of parts (Ruffo & Hague, 2007), doubting constant manufacturing costs. As recently investigated by Baumers and Holweg (2019), static economies of scale occur for the AM build volume, just like for traditional manufacturing. The better the build volume is utilized, the more fixed machine setup costs can be spread across parts. Nevertheless, the current cost structures of AM limit the possibility of cost reductions for high volumes compared to traditional manufacturing technologies.

Another recognized challenge is the **quality**, **accuracy**, and **reliability** of the AM process. The concerns relate primarily to the product quality, which heavily depends on the selected AM technology (Ngo et al., 2018). The layer-by-layer process may not fulfill the requirements of a specific application, such as the surface conditions or the mechanical properties. Thus, extensive post-processing may be necessary, or AM may not be applicable for the corresponding product at all (Zijm et al., 2019). Moreover, there is a lack of industry-wide standards at the current emerging stage of AM technologies. As a result, internal documentation and individual procedures for quality inspections are used to identify defective components, which complicate quality control (Thomas-Seale et al., 2018). Quality concerns also refer to the process quality of AM. Reliable, stable, and reproducible manufacturing processes must be guaranteed, and this is not the case for AM yet (Gibson et al., 2015). In-process monitoring tools to assess the process quality are still lacking (Thomas-Seale et al., 2018). Thus, there is an overall need for advances in the standardization of AM (e.g., calibration, monitoring, testing procedures, and file formats), and this is a prerequisite for the industrialization of the technologies (Gao et al., 2015). Institutions from different countries, such as ASTM from the US or ISO from Switzerland, have started to publish initial standards in this regard (Featherston et al., 2016).

Additional **technical constraints** of AM pose challenges for firms. These include the limited range of materials standardly available for AM compared to the great variety of materials for traditional manufacturing technologies. If demanded materials are currently not available for AM, parts are not additively manufacturable at all or need to be matched with and potentially redesigned for alternative materials (Kretzschmar et al., 2018). Material prices remain high at the current emerging stage (Berman, 2012; Mellor et al., 2014), and developing new materials for AM is costly and time-intensive based on strict regulations in the industrial context (Durach et al., 2017b; Thomas-Seale et al., 2018). Moreover, only a few AM machines can currently manufacture multiple materials simultaneously (Sitthi-Amorn et al., 2015). Constraints in the build volume and the relatively low production speed further limit the efficiency of specific AM technologies (Gibson et al., 2015; Kretzschmar et al., 2018). While increasing the layer thickness shortens the build time, it also reduces the accuracy, which, in turn, may entail additional post-processing steps (Rosen & Kim, 2021).

Challenges also arise within organizations in terms of **education** and **acceptance** of AM. At the current emerging stage, there is a lack of trained and experienced AM specialists in firms due to the novelty of the technologies (Gao et al., 2015). While the process of additively manufacturing a part is expected to be highly automated, skilled engineers are needed for the digital domain of the technologies (Ben-Ner & Siemsen, 2017). This includes, in particular, the (re-)designing of components for AM and the handling of the design software. An essential aspect is that employees cannot rely on their traditional design knowledge and expertise for AM but require new and different skills (Mellor et al., 2014). With limited established education programs for AM, firms currently face knowledge gaps and are challenged to find specialists on the labor market (Thomas-Seale et al., 2018). Finally, problems of acceptance must be overcome in emerging AM. Changing employees' mindsets and gaining acceptance for the novel manufacturing process are essential milestones for broadening AM applications (Huang et al., 2015).

Table 2-2: Advantages and challenges of industrial AM.

| Advantages | Challenges |
|---|---|
| **Freedom of design:**<br>▪ Unlimited complexity in designs<br>▪ Functional integration and process integration | **High costs:**<br>▪ High costs for part consolidation (fewer, more complex parts reduce the flexibility)<br>▪ High costs for AM machines and materials<br>▪ Minor relevance of economies of scale in AM |
| **"Complexity for free":**<br>▪ No additional unit costs for complex designs<br>▪ Highly automated manufacturing process with little manual labor input<br>▪ Expected increase in the automation of pre- and post-processing | **Quality, accuracy, and reliability:**<br>▪ Unstable product quality<br>▪ Extensive post-processing<br>▪ Lack of industry-wide standards<br>▪ Need for more robust AM machines and monitoring tools |
| **General-purpose AM machine:**<br>▪ No fixed costs for product-dependent setup and tooling<br>▪ Shortened time to market<br>▪ No geographic ties of production<br>▪ Transportable AM production units | **Technical constraints:**<br>▪ Limited range of materials, high prices, and lengthy development of new materials<br>▪ Build volume limits the size of manufacturable components<br>▪ Relatively low production speed |
| **Resource efficiency:**<br>▪ Reduction of waste based on the additive process<br>▪ High recycling rate of excess material<br>▪ Sustainability advantages in the product life span | **Education and acceptance:**<br>▪ Need for skills in the digital domain (design for AM, software handling)<br>▪ Limited education programs for AM<br>▪ Problems of gaining engineers' acceptance |

### 2.1.4 Fields of application

The presented advantages and challenges determine the current fields of application of AM in industry. The low upfront costs paired with the inherent flexibility of general-purpose AM machines make the digital technologies an ideal candidate for low-volume, high-variant, or high-complexity contexts (Conner et al., 2014; Feldmann & Pumpe, 2017). These three fields of application for AM are proposed in the literature and visualized in Figure 2-4. According to Conner et al. (2014), AM requires additional advantages to become the option of choice for the combination of low-volume, low-variant, and low-complexity parts (see Figure 2-4). In such a case, lower costs and reduced lead times could be decisive for AM (Conner et al., 2014).

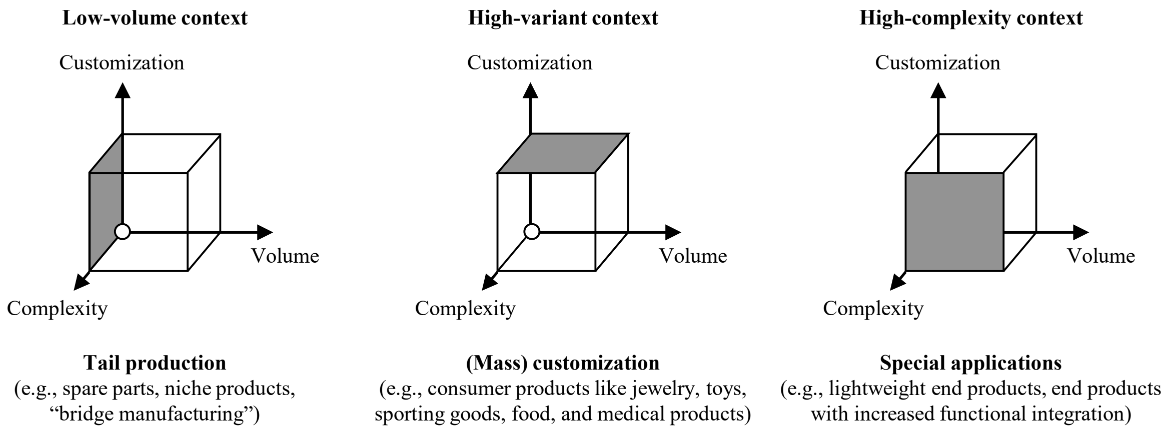



Figure 2-4: Fields of application for AM (based on the model introduced by Conner et al. (2014)).

**Low volumes:** AM enables the manufacturing of niche products. Anderson's (2008) long tail thesis states that the number of the products and services offered is only a small percentage of the actual range of available products and services in many markets. In bookstores or music stores, for example, only a small fraction of commonly available books or music can be purchased. The Internet has enabled online retailers such as Amazon and streaming platforms like Spotify to make niche products visible to customers and offer them economically. Thus, it follows the principle of "selling less of more," which goes back to the title of Anderson's (2008) book. As a result, previously unknown, smaller customer segments can be addressed (Sasson & Johnson, 2016). This phenomenon also applies to AM as the technologies are suitable for manufacturing small volumes of less commonly demanded products economically (Holmström & Partanen, 2014; Pérès & Noyes, 2006). A prime example for single parts or small volumes are spare parts, and AM has the potential to address key challenges of these applications, including capital-intensive inventory and obsolescence problems (Khajavi et al., 2018). A further example in the industrial context is the manufacturing of small volumes in the period between design completion and the start of mass production. The use of AM makes it possible to "bridge" this phase, termed "bridge manufacturing." This is a lucrative option for firms that are confronted with complex, costly, and time-consuming tooling operations. Firms may be in need of financing the setup of mass production (e.g., the manufacturing of molds and tools) with already realized sales of the product, and AM is advantageous in such a situation (Berman, 2012). Moreover, additively manufactured parts can be used to detect mistakes and make corrections in the assembly line before the start of serial production (Gibson et al., 2015). These examples of the low-volume context, again, underline the suitability of traditional manufacturing technologies to serve high customer demand.

**High variants:** Customization is a huge challenge in traditional manufacturing. Parts need to be standardized to keep the capital costs of production lines and fixed costs for tooling and fixtures low. Consequently, manufacturing firms commonly focus on mass manufacturing to achieve cost reductions per manufactured unit at a high production rate. However, the flexibility of AM enables (mass) customization. Individual products for specific customers or purposes without a significant increase in the unit costs shift the focus of AM to the created customer value. This contrasts with the common focus on cost reduction of mass manufacturing (Conner et al., 2014). In practice, customization is needed more for consumer applications than in industry. Application fields for customization to the single customer ("personalized manufacturing") exist, primarily in medicine, jewelry, toys, sporting goods, and food (Kwak et al., 2018). Famous examples include the in-store 3D printing of customized shoes at retailers and individualized medical and dental components (Berman, 2012).

**High complexity:** The high complexity of components is associated with high costs in the context of traditional manufacturing based on, for instance, additional manufacturing and assembly steps. In contrast, AM has demonstrated its potential to economically manufacture highly complex applications. This has proven to be beneficial for the manufacturing of end products in specific industries (Conner et al., 2014). For instance, Atzeni and Salmi (2012) demonstrate the advantageous use of complex, metal AM parts for aircraft landing gears. They describe how firms can benefit from the freedom of design (e.g., with variable wall thicknesses and cooling channels) and minimize part count by functional integration.

In summary, this section has provided an understanding of AM technologies and outlined their fundamental differences from traditional manufacturing technologies. As AM has rapidly grown since the late 1980s and raised media attention, firms have been increasingly confronted with the question of how to make use of the emerging digital technologies in their operations to gain and sustain a competitive advantage. The next two sections build a literature-based understanding of why industrial AM creates an impetus for traditional SC actors, particularly LSPs and manufacturing firms, to adapt their business models and their traditional SCDs.

## 2.2 Business model development for additive manufacturing

This section provides the background for investigating the impact of AM on incumbents' business model development with a focus on LSPs and structures previous research in this domain. First, in Section 2.2.1, a business model perspective is applied to outline the fundamentals of the business model concept. Section 2.2.2 follows with an introduction to the business ecosystem for industrial AM as the context in which AM business models emerge. Section 2.2.3 then motivates the impulse provided by AM for the traditional business models of incumbent firms. On this basis, Section 2.2.4 analyzes the AM business model literature with a focus on LSPs.

### 2.2.1 The perspective of business model research

The business model terminology has gained momentum since the late 1990s due to the development of information and communication technologies and the emergence of Internet firms (DaSilva & Trkman, 2014; Osterwalder et al., 2005). A business model is described as a "way of doing business" (Voelpel et al., 2004, p. 261), as a "blueprint" (Osterwalder et al., 2005, p. 2), or as a "recipe" (Baden-Fuller & Haefliger, 2013, p. 425). It is essential for the commercialization of products and services as it provides a "coherent framework" that "mediates between technology development and economic value creation" (Chesbrough & Rosenbloom, 2002, p. 532). Research on business models has so far mostly focused on the static outcome of **"finished" business models**. This perspective facilitates identifying and defining the central components of business models, developing classifications, and investigating the relationship between a given business model and the performance of a firm (Demil & Lecocq, 2010). For example, value creation, value proposition, and value capture are commonly considered to be business model components that are interpreted for specific business models (Amit & Zott, 2015; Baden-Fuller & Haefliger, 2013). However, there is a growing body of literature acknowledging that it is necessary to understand not only the static outcome of a business model but also how it changes (e.g., Cavalcante et al., 2011; Cavalcante, 2013; MacInnes, 2005; Voelpel et al., 2004). Following Afuah and Tucci (2003) and Rong et al. (2018), this thesis refers to **business model dynamics** for the activities associated with changes in existing business models over time. The novel stream of literature dealing with business model dynamics is closely tied to emerging technologies (Adner & Levinthal, 2002), nascent markets (Rask & Günzel-Jensen, 2019), and business model innovation (Chesbrough, 2007). It is based on the assumption that successful business models do not persist forever but require firms to continuously experiment and search for ways to innovate their business models (Chesbrough, 2007).

**Discontinuities in firms' environments** are recognized as major exogenous drivers that trigger and necessitate business model dynamics. The literature highlights technological advances or disruptions and market-related forces as initiators of business model dynamics (Baden-Fuller & Haefliger, 2013; de Reuver et al., 2009). In this vein, Voelpel et al. (2004) point out that fast-changing business environments, as evident today, create uncertainty and unpredictability. They suggest that changes in business models are required to secure firms' survival and sustained competitive advantage in such environments. Implemented changes in business models can differ in their extent, basically from adjusting an existing business model to designing an entirely new business model (Baden-Fuller & Haefliger, 2013). The literature proposes the term "business model innovation" for the case that firms implement a new business model that fundamentally differs from business models that are traditionally established in an industry (Rask & Günzel-Jensen, 2019). MacInnes (2005) highlights that the extent of business model change is based on the perceived character of the exogenous threat. For instance, it may be feasible to integrate sustaining technologies into existing business models, while disruptive technologies are more likely to require new business models. In the case that a technology has just been discovered or developed and is in an early emerging stage, creating a business model may not even be possible yet. Firms might need to overcome technical problems (e.g., ensuring a minimum standard performance) and environmental problems (e.g., copyright violations) before they can commercialize a technology (MacInnes, 2005).

The business model research highlights that changing existing business models in light of the threats from emerging technologies is difficult to achieve. Incumbent firms face significant **barriers** to changing their business models. For instance, Chesbrough (2010, p. 359) argues that firms tend to follow a "dominant logic" in their value creation, which may prevent noticing potential new business opportunities. Similarly, Cavalcante (2013, p. 287) outlines how the "path dependence" of firms, for example, established organizational routines, hinders dynamically changing business models. Sull (1999, p. 43) calls the phenomenon "active inertia" and describes it as "an organization's tendency to follow established patterns of behavior – even in response to dramatic environmental shifts." Firms are entrenched in their managerial routines, traditional mindset, way of thinking and acting, and deeply committed to their established business models (Voelpel et al., 2004). Furthermore, conflicts between established business models and novel business models to exploit emerging, potentially disruptive technologies may arise and prevent changes (Chesbrough, 2010). Interestingly, Christensen's (1997) "The Innovator's Dilemma" initially established the understanding that technologies themselves are the reason why incumbents fail to adapt in light of technological change. Later, in 2006, his correction – "It is a business model problem, not a technology problem" – clarified that tensions between established business models and the novel ones hinder incumbents from succeeding when disruptive technologies emerge (Christensen, 2006, p. 48).

The likely hesitation and struggle of incumbents, however, constitute a significant **competitive advantage for new entrants** (Voelpel et al., 2004). In this sense, the business model literature consistently argues that new entrants are better suited to commercialize emerging technologies than incumbents (e.g., Anderson & Tushman, 1990; McGrath, 2010; Rask & Günzel-Jensen, 2019). Common advantages of new entrants include their smaller firm size, shortened path-dependent history, less partially irrelevant knowledge and assets, and limited commitment to existing value chains and technological paradigms (Henderson & Clark, 1990; Macher & Richman, 2004). Moreover, new entrants are expected to outperform incumbents with their flexibility in marketing strategies and shorter time to market (Walsh et al., 2002). As a result of the described barriers and weaker position than new entrants, incumbent firms may be reluctant to change their deep-rooted business models (Chesbrough, 2010). They may refrain from renewing themselves completely and rather implement small business model changes (Cavalcante, 2013). In this vein, Teece (2018) emphasizes that firms often rely on past investments and existing organizational structures to create permutations of existing business models. Business model variants that fit existing business models are assessed as easier to implement. On the downside, Teece (2018) notes that such slight adaptations are rarely sufficient to regain a competitive advantage when it is at risk.

To **overcome incumbents' reluctance** to business model change, the business model literature advises firms to start initiating, experimenting, and developing new business models accompanied by a mindset for organizational change (Chesbrough, 2007, 2010). This is described as an ongoing and iterative process, often based on trial-and-error learning and a willingness to leave the organizational "comfort zone" (Rong et al., 2018). For example, Voelpel et al. (2004) propose a process of customer sensing, technology sensing, business infrastructure sensing, and economic/profitability sensing. They advise firms to undergo such a process along with the management of their traditional business models. This results in a continuous process of co-shaping and co-managing existing and modified or newly established business models. In a similar vein, other studies propose cyclical concepts of business model change to demonstrate the continuity of the process (Amit & Zott, 2016; Chesbrough, 2010; Demil & Lecocq, 2010). Hence, it takes time for business models to catch up on novel, potentially disruptive technologies (Teece, 2018), and this is true for AM as well, as described next.

### 2.2.2 The business ecosystem for industrial additive manufacturing

Since the late 1980s, AM technologies have been successively commercialized by newly established AM equipment providers, who can be seen as the "enablers" of AM. The novel and potentially revolutionary characteristics of AM have also triggered the emergence of new products and services. A large number of new entrants have started to enter the nascent AM market to fill emerging product and service niches, as entry barriers are currently still comparably low (Ben-Ner & Siemsen, 2017; D'Aveni, 2015; Rosli et al., 2017). Their roles in the AM business ecosystem can be described as "supporters" of AM adoptions and implementations. In terms of firm size, it is conspicuous that the AM market has attracted a wide range of startups in recent years (AMPOWER, 2021b; Rogers et al., 2018), and these new players from the AM domain have achieved many of the technological breakthroughs of industrial AM (Bechtold, 2016). In addition, larger established incumbents have started to enter the AM market not just as industrial users of the technologies but also as providers of AM-specific services and products (D'Aveni, 2018; Mohajeri et al., 2016). Rogers et al. (2018) find that both incumbents and new entrants from the AM domain raise the competitive pressure in the AM market. In 2020, independent service providers (i.e., service providers that are not part of AM machine manufacturers) generated an estimated worldwide revenue of $5.270 billion by selling additively manufactured parts, 7.1% more than in 2019 despite the COVID-19 crisis (Wohlers Associates, 2021b). This indicates the considerable size of the AM service market. According to Rong et al. (2018), a strong business ecosystem has evolved for AM. Generally speaking, a business ecosystem is characterized by firms that "co-evolve capabilities around a new innovation" (Moore, 1993, p. 76). Beltagui et al. (2020) provide in a longitudinal narrative study an overview of how the AM business ecosystem has evolved since the first patents. To demonstrate the current status, Figure 2-5 presents a map of the industrial AM business ecosystem and illustrates major actors and their primary products and/or service offers. The following paragraphs describe these actors of the business ecosystem for industrial AM, starting with the new entrants.

**New entrants** include AM equipment providers and AM service providers (see Figure 2-5). **AM equipment** providers can be divided into hardware providers (i.e., AM machine manufacturers, AM material suppliers, and 3D scanner suppliers) and software providers (Holzmann et al., 2020a; Li et al., 2017a). In this context, equipment for industrial AM machines must be distinguished from "desktop" polymer 3D printers (Holzmann et al., 2020a) that are situated in the consumer market (e.g., for home fabrication, see Section 2.1.1). Among AM material suppliers, photopolymers used to be the largest market segment based on their famous use for prototypes (Wohlers Associates, 2021b). However, in 2021, they were overtaken by polymer powders (Sertoglu, 2022). 3D scanner suppliers offer a range of scanning devices, starting with scan applications for smartphones, to mobile handheld scanners, and stationary scanners (Holzmann et al., 2017; Raja & Fernandes, 2008). In terms of AM software providers, a differentiation can be made between the design (CAD software) and the process of slicing and defining AM machine settings (CAM software), as described in Section 2.1.2. Software firms also provide technical solutions for secure data transfer to the AM machine and handling during the AM process. Specialized software products may, for instance, also include 3D model viewers, support for the repair of redesigned objects, scheduling for AM jobs, and support for AM machine users with aftersales services (Rogers et al., 2018). Several software providers offer integrated solutions that aim at covering the whole AM workflow, for instance, 3DXpert from 3D Systems (3D Systems, 2022).

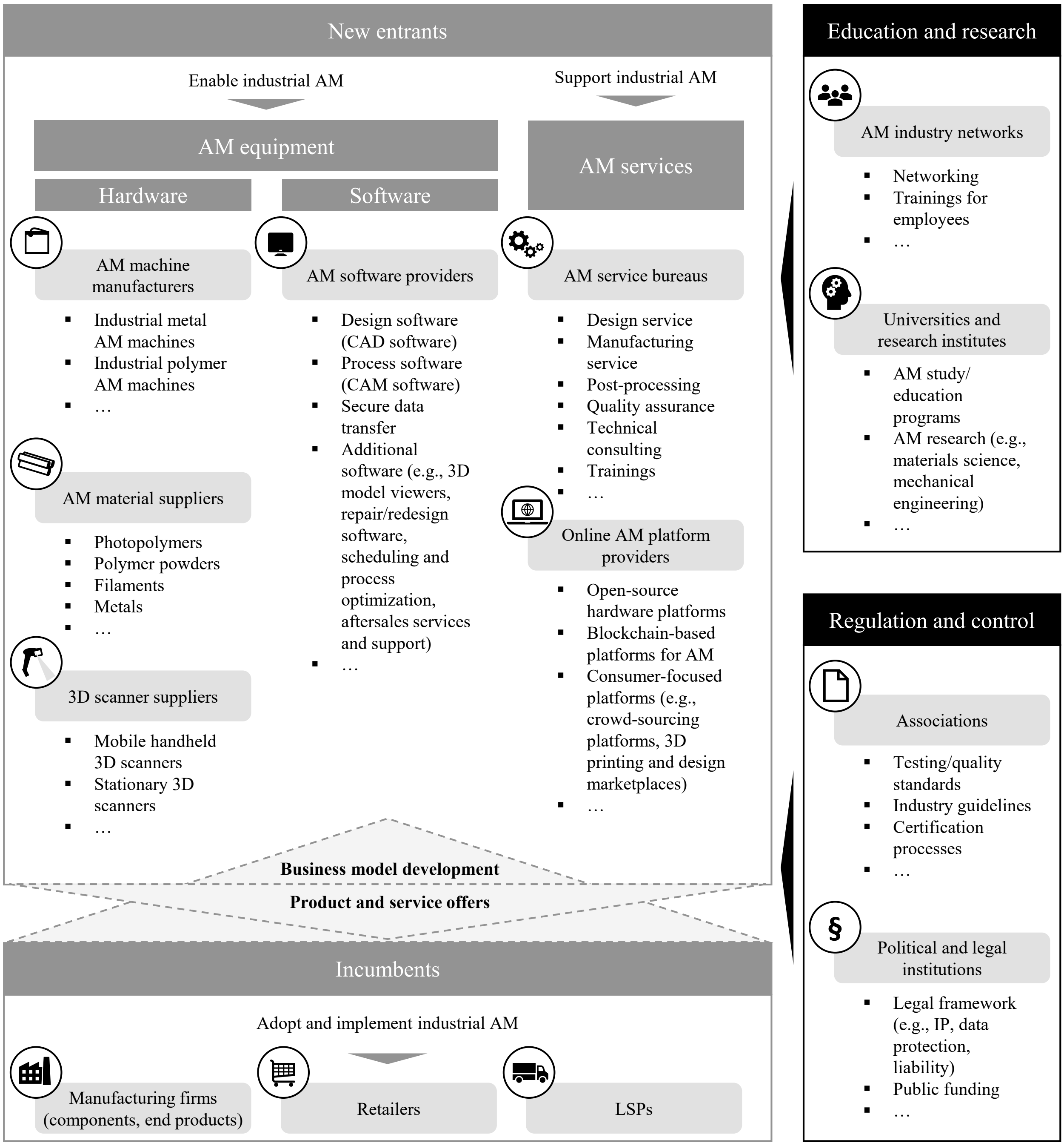



Figure 2-5: The business ecosystem for industrial AM.

**AM services** support incumbent firms in their adoption and implementation of AM. They are commonly offered by AM service bureaus. At their core, AM service bureaus provide manufacturing services for AM, combined with complementary services like design, post-processing, quality assurance, consulting, and training of employees. Commonly, AM service bureaus bundle these services, which result in unique combinations for the individual customer (Rayna et al., 2015; Rogers et al., 2016). Note that AM service bureaus – in their role as contract manufacturers – differ from 3D print shops that denote small stores with a limited number of "desktop" 3D printers for selling parts locally and primarily to end consumers (Wohlers Associates, 2021b). What is more, the offers of AM service bureaus oftentimes overlap with online AM platform providers, which are established for similar purposes. Online AM platform providers offer a spectrum of entirely digital services (e.g., AM design services) or a combination of partly digital and physical services (e.g., design and manufacturing services). Thus, they are broadly characterized by their ability to "combine both elements of 'pure' digital services […] with elements of 'traditional' e-business related to online purchase of physical products" (Rayna & Striukova, 2016c, p. 155). Famous examples include open-source hardware platforms (e.g., the "RepRap" community[8]), which have stimulated the evolution of affordable polymer 3D printers (Kwak et al., 2018). Furthermore, project consortia have been established, for example, for developing blockchain-based AM platforms (Kurpjuweit et al., 2021). Potential use cases for such platforms include secure AM outsourcing, capacity sharing of AM machines, and the involvement of external designers in the AM design process. Such direct interactions are currently still underrepresented in industrial AM (Klöckner et al., 2020). A rare example is the public idea contest of General Electric for a lighter jet engine bracket design, which resulted in a weight reduction of 84% of the component (Troxler & van Woensel, 2016). In comparison, on the consumer side of AM technologies, a broader spectrum of platforms facilitates consumer co-creation and consumer innovation. These platforms range from design marketplaces to crowdsourcing platforms and aim to empower consumers to take an active role in the design and manufacturing processes (Kwak et al., 2018; Rayna et al., 2015). With that, they foster the transition from consumers to "prosumers"[9] and fuel the growing "Maker/Do-It-Yourself" community (de Jong & de Bruijn, 2014; Halassi et al., 2019). Design platforms like Thingiverse have reported more than 2.3 million uploaded 3D models for personal use in 2022 (Thingiverse, 2022). In addition to such digital services, physical fabrication spaces, termed "fab-spaces" or "fab-labs," have emerged to provide private persons, entrepreneurs, and small firms shared access to professional AM equipment and knowledge (Mortara & Parisot, 2016; Santos et al., 2018).

**Incumbents** with established business models in the traditional manufacturing market include foremostly manufacturing firms (i.e., end-product and component manufacturers), retailers, and LSPs (see Figure 2-5). These actors fulfill a twofold role in the AM business ecosystem. As adopters and implementers of AM, they are the predestined industrial customers addressed in the product and service offers of new entrants from the AM domain. However, examples show that they also see potential in the development of their own business models in the AM market. Large, multinational manufacturing firms like General Electric, Airbus, Boeing, Bugatti, BMW, and Siemens have started to enter the AM market as producers and service providers (Mohajeri et al., 2016). Commonly, these firms have realized mergers with or acquisitions of firms with specific AM competencies to position themselves in AM (Rogers et al., 2018). For example, Siemens acquired the metal AM specialist Materials Solutions to offer high-tech engineering and manufacturing services (Siemens, 2018). Similarly, General Electric acquired majority stakes of Arcam and Concept Laser (GE Additive, 2016). SMEs from the traditional manufacturing domain are, so far, more hesitant to enter the AM market, mostly due to a lack of substantial financial and intellectual resources. They are limited in their ability to realize mergers or acquisitions and to flexibly exit the AM market in case of an unsuccessful positioning (Martinsuo & Luomaranta, 2018; Rogers et al., 2018). Larger retailers have also started to include AM-specific products into their portfolios by focusing on the

[8] "RepRap" (replicating rapid prototyper) is an open-source community with the purpose of creating self-replicating 3D printers. Design files are shared and enable the community to 3D print polymer parts of the "RepRap" 3D printer and, thus, self-replicate it (de Jong & de Bruijn, 2014).

[9] The term "prosumer" is composed of the words "consumer" and "producer." According to Halassi et al. (2019), it demonstrates the participation in both production and consumption.

consumer side of the technologies. For instance, the online shops of Amazon and Walmart offer a wide range of equipment for consumer polymer 3D printing (Amazon, 2022; Walmart, 2022). Trials with in-store 3D printing for on-demand customized products are underway, including sneakers (e.g., of Adidas, Reebok, and New Balance) (Gregurić, 2020) and self-designed clothes (e.g., Ministry of Supply) that are manufactured with a 3D robotic knitting machine (Schiffer, 2017). Similarly, LSPs have started to enter the AM market. Most famously, UPS installed polymer 3D printers in initially 60 UPS stores for consumer products in 2013. In addition, it acquired a minority stake of Fast Radius, a specialist capable of manufacturing additively at an industrial level (Berman, 2016; Scott, 2016).

Figure 2-5 indicates that the AM business ecosystem is embedded in its **environment**, including social, technological, legal, and political organizations and institutions. For instance, Xu et al. (2018) demonstrate interrelations between the business sub-ecosystem and the science and technology sub-ecosystems for the Chinese AM industry. In Figure 2-5, interrelations with public and non-public organizations that are responsible for education and research as well as for regulations and control are highlighted. These organizations foster the industrialization of AM by building specific knowledge and by driving advances in the development of industry guidelines and a legal framework for AM (Piller et al., 2015).

The introduced AM business ecosystem forms the context in which AM business models evolve (Rong et al., 2018). As demonstrated with the examples above, emerging AM encourages incumbents or even urges them to enter the AM business ecosystem, not just as industrial users, but with new or adapted business models, as long as the market entry barriers remain comparatively low. However, it should be borne in mind that the **emerging stage** and **nascent market** of AM technologies not only foster but also complicate the establishment of profitable business models for incumbents. The dynamics of AM entail that there is little consensus about the capabilities required for AM business models, and uncertain demand hinders significant investment in AM-specific resources (Rong et al., 2018). Moreover, conflicts with incumbents' existing business models may emerge, and management perceptions may prevent understanding these conflicts (Bogers et al., 2016), in line with the general discussion in the business model literature (see Section 2.2.1). Another aspect is that incumbents face the duality of being equipped with their existing resources (e.g., employees and organizational structures) while trying to make use of AM. Indeed, AM requires employees with different competencies (e.g., with more analytical, integrative, and creative skills) for the AM design process. Ben-Ner and Siemsen (2017) propose that AM technologies will disrupt the labor market, and firms are challenged in the transition of adapting to AM while dealing with their existing workforce and organizational structures. In addition, Roscoe et al. (2019) emphasize that the appropriate organizational structure for AM lies outside the authority-based structures of firms' traditional business. They propose a more flexible integration of AM within firms (e.g., in competence centers) to foster trial-and-error learning and knowledge exchange. This is also reflected by new entrants from the AM domain that typically have smaller, more flexible work organizations. Besides, most of these firms are "born digital"; thus, they are not entrenched in their traditional "analog" business (Holzmann et al., 2020a, p. 1294).

A further aspect that might be misleading is that Figure 2-5 gives the impression of a clear and balanced structure of the AM business ecosystem. In reality, where customer demand remains uncertain for now, the **positions of actors are not static** (yet). This leads to a great variety and heterogeneity of services and products. Significant overlaps in the actors' positions make it difficult to allocate suitable business opportunities. For example, AM machine manufacturers partly also offer manufacturing services (e.g., voxeljet and ExOne). Thus, they position themselves as service bureaus and AM machine manufacturers (ExOne, 2022; Voxeljet, 2022), which raises the competitive pressure for independently operating AM service bureaus (Wohlers Associates, 2021b). Moreover, AM machine manufacturers also move into the market of "desktop" 3D printers and online design communities, as observable by Stratasys' acquisition of MakerBot (Clay, 2013). AM service bureaus, on the other hand, partly also operate marketplaces for AM equipment (e.g., Filafarm) (Filafarm, 2022). Other examples include AM machine manufacturers that assume the role of AM material suppliers to develop and sell exclusive materials for their specific AM machines (Cohen et al., 2014; Kietzmann et al., 2015). The proprietary or licensed materials enable them to extract value from the use of AM machines and to stay in ongoing relationships with their customers, which relates to a "razor and blade" business model (Amit & Zott, 2015; Teece, 2010). According to Rong et al. (2018), the currently observable overall overlapping results in mixed ecosystem structures that are characterized by a high ambiguity and complexity.

In summary, this section has provided an overview of how new entrants and incumbents are in the process of forming an AM business ecosystem. However, the emerging stage of the technologies and the unstructured and fast-moving market setting pose challenges for the development of AM business models. As a result, systematizing how competitive positions emerge in the AM business ecosystem is associated with considerable difficulties, as also emphasized by Savolainen and Collan (2020a). The next section will shed light on the promises AM holds for the business model development of incumbents and highlight the special position of LSPs.

### 2.2.3 Impulse given by additive manufacturing for business model development

Despite the challenges that come with the formative stage of the AM business ecosystem, the expectations for AM to revolutionize traditional business models are high: Jiang et al. (2017, p. 93) expect the disruptive power of the technologies to force incumbents to make "radical changes" to their traditional business models, and Bugdahn et al. (2019) call for a transformation of existing business models based on AM. In a similar vein, Bogers et al. (2016) propose that reshaping or reinventing incumbents' business models may be required to capture the value of AM and stay competitive. Incumbents are expected to fight to "build, maintain and defend" their positions in AM (Öberg, 2019, p. 174). Thus, adjusting existing and developing novel business models for AM is perceived as necessary in the literature. Rayna and Striukova (2016b, p. 224) even assess it as a prerequisite for building a competitive advantage in AM by stating, "winners of tomorrow are those companies which, far from being blindsided by the new technology, will think first and foremost in terms of business model innovation."

The impulse given by AM for incumbents' business model development results from the inherently digital and flexible nature of the technologies. The digital characteristics of AM emphasize digital assets (i.e., AM designs and required software and IT solutions) and employees' capabilities to exploit the novel design options in the value creation process (Ben-Ner & Siemsen, 2017; Hahn et al., 2014). In contrast, the requirements and relevance of the physical elements of AM are low. As is typical for digital technologies, the "physical 'expression' generally mattered little if at all" (Rayna & Striukova, 2016b, p. 214). For AM, this is reflected by the basic, unspecific raw materials and general-purpose AM machines that are the necessary physical assets for the ideally one-step process of transforming the digital product specification into a physical product. With the increasing automation of this process and easy-to-acquire competencies (see Section 2.1.3), the core value of AM lies in the digital domain, the creation of the digital product specification. This definition of value in AM changes the way incumbents can create, appropriate, and capture value compared to traditional manufacturing technologies. Table 2-3 summarizes the new opportunities and challenges that come with AM for the three commonly considered business model components (see Section 2.2.1), as detailed next.

**Value creation:** The digital characteristics of AM lead to the distinction between products and services to lose its importance (Savolainen & Collan, 2020a; Troxler & van Woensel, 2016). Termed "digital servitization," digital technologies like AM can advance the general shift from selling physical products to embedding them in novel customer-oriented bundles of digital services (Paschou et al., 2020). Vice versa, AM is expected to enable service providers (e.g., UPS) and retailers (e.g., Amazon) to turn into manufacturers based on the robustness and reduced requirements for the AM process, termed "productization"[10] (Eyers et al., 2019). Hence, AM machines hold the promise of being accessible for firms without relevant manufacturing backgrounds like LSPs (Durach et al., 2017b; Holmström & Partanen, 2014) and retailers (Arbabian & Wagner, 2020). This enables manufacturing firms, retailers, and LSPs to move back and forth on the continuum of product-service systems[11], see Purvis et al. (2021). Such an understanding changes the traditional roles of incumbents. For example, Cautela et al. (2014, p. 497) observe that firms "often surpass the traditional vertical relationships between producers and distributors" in AM. Hence, AM shrinks not only the gap between products and services but also blurs the established boundaries between the business models of incumbents (Lipson & Kurman, 2013; Savolainen & Collan, 2020a). Moreover, the digital nature of AM suggests that business models evolve from close and manufacturer-centric to open and customer-centric. It is again the low skill barriers for the AM process, coupled with the ease of sharing the digital designs, that foster the active integration of customers into the value creation process, as already evident on the consumer side of AM (Christopher & Ryals, 2014; Durach et al., 2017b). With AM being part of the "automation-driven 'industry 4.0'-paradigm" (Savolainen & Collan, 2020a, p. 2), co-creation may also become increasingly feasible for industrial AM and lead to "self-services" of industrial customers (Rogers et al., 2016, p. 898). Finally, the flexibility of general-purpose AM machines and the ability to manufacture small volumes economically (see Section 2.1.3) suggest that not only AM technologies but also AM business models can become location-independent (Bogers et al., 2016). The AM machine serves as a complementary asset that can ideally be used to manufacture any digitally transferred design, regardless of its location. Consequently, business models themselves are expected to become "mobile," "modular," and "adaptable" (Rayna & Striukova, 2016b, p. 221). In the broader picture, location-independent AM is key for enabling a shift from centralized, large-scale manufacturing plants to decentralized, small-scale production close to or even at the point of demand (Durach et al., 2017b).

**Value proposition:** Manufacturing firms are the primary incumbents to leverage the specific characteristics of AM by moving from their traditional patterns based on economies of scale and centralized production to more small-scale, decentralized, and more inclusive settings (Bogers et al., 2016; Durach et al., 2017b). This foreseen development is expected to enable manufacturing firms to address niche markets with AM (e.g., in low-volume, high-variant, or high-complexity contexts, see Section 2.1.4) that are not accessible with traditional large-scale manufacturing (Rayna & Striukova, 2016b). Furthermore, decentralized AM holds the potential for manufacturing firms to improve the service level for their industrial customers, for example, by reducing lead times of (critical) spare parts with decentralized AM. As an additional implication, decentralized AM may enable circular economies (Despeisse et al., 2017a; Hettiarachchi et al., 2022) and unlock positive social effects on local employment and workforce qualification (Cardeal et al., 2020). From the perspective of retailers, the characteristics of AM suggest placing the transportable and compact AM production units (see Section 2.1.3) directly in retail stores. Such an envisioned positioning of AM in retail stores fuels, again, the concept of distributed, small-scale production close to the final customer. To be more specific, AM in retail stores holds the potential to enable on-demand production of mass customized parts (Laplume et al., 2016). This is an opportunity for increasing customer value through differentiation and responsiveness, and such advantages are expected to outweigh higher production costs (Arbabian & Wagner, 2020). In addition, AM in retail stores is likely to reduce inventory and transportation costs (Jia et al., 2016). Only low-cost, low-value raw materials need to be stocked for AM. Thus, there is a clear contrast between AM business models and traditional brick and mortar retailers that require high sales volumes and an extensive work-

[10] "Productization" describes the strategy of how firms with traditionally strong service capabilities add a tangible product to their offering (Eyers et al., 2019; Lahy et al., 2018).

[11] A product-service system consists of tangible products and intangible services that are combined to jointly fulfill a specific customer demand (Lahy et al., 2018; Tukker, 2004).

force to handle the transaction volumes and keep shelves stocked (Laplume et al., 2016). To sum up the expected effect, "Retail as we know it might disappear to a large extent. There would be no need for stocking up on single items for 'retailers' […], and no need for manufacturers to 'feed' the retail chain for an unknown or quickly changing demand" (Troxler & van Woensel, 2016, p. 199).

**Value capture:** With the novel ways of creating and appropriating value in AM also comes the need for new and adapted revenue mechanisms that account for the specifics of these technologies. For example, customization permits price increases for the additional value offered despite little or no cost penalties in the manufacturing process (Baumers & Holweg, 2019). Co-creation also needs to be considered in pricing models since it is likely to lead to increasing customer reluctance to pay the full price (Rayna & Striukova, 2016b). Besides price structures, internal cost structures for AM business models change with no fixed costs for tooling and product-specific setup (Weller et al., 2015). With economic, small-scale manufacturing close to or even at the point of demand, further reductions of fixed costs, e.g., for transportation and warehousing, can be realized (Kleer & Piller, 2019). Another factor to be considered is that the digital nature of AM entails novel risks in terms of copyright violation and IP protection (Appleyard, 2015). The encapsulation of the core value of AM in the digital product specification and the ease of sharing and distributing digital files pose challenges for the design of revenue mechanisms and contractual arrangements. Similar concerns have already been raised in other digitally dominated industries (e.g., music, encyclopedias, video games, and online news). Since all of these industries rely on the digital representation (e.g., design, music, or news files) of firms' IP (Appleyard, 2015; Troxler & van Woensel, 2016), relatively limited financial investments are necessary to exploit the digitally held IP (e.g., a general-purpose AM machine and basic raw material). Consequently, barriers against piracy decrease, creating new copying and counterfeiting risks (Bechtold, 2016; Piller et al., 2015). For example, Chan et al. (2018, p. 158) raise the fear for AM, "it is easier than ever before to 'steal' a product design." However, it is still acknowledged to be significantly more difficult to master potentially multiple AM technologies than copying music or video files (Appleyard, 2015; Kapetaniou et al., 2018).

Table 2-3: Expectations for AM business models.

| Value creation[12] | Value proposition[13] | Value capture[14] |
|---|---|---|
| ▪ **From products and services to product-service systems:** Blurred borders between products and services ("servitization" and "productization") and surpassing of traditional vertical relationships<br>▪ **From close to open:** Integration of customers (co-creation) into the value creation process<br>▪ **From central to decentral:** Location independence of AM enables small-scale, on-demand manufacturing close to or even at the point of demand | ▪ Addressing of **niche markets** (low volumes, highly customized or complex parts)<br>▪ Improving of **service level** (e.g., lead time reduction for decentrally manufactured spare parts)<br>▪ Enabling of **circular economies** and positive **social effects**<br>▪ Enhancing of **responsiveness** and **differentiation** (e.g., by manufacturing postponement and final customization according to the customer preferences at retail stores) | ▪ **Pricing models** have to account for the specifics of AM (e.g., co-creation, customization)<br>▪ Different **cost structures** (e.g., economically viable, small-scale production/ decentral production)<br>▪ **IP protection** (risk of copying and counterfeiting) requires technical solutions and AM-specific contractual arrangements |

[12] The value creation describes how a firm and its partners utilize their resources to create value for the targeted customers (Cachon, 2020).
[13] The value proposition describes the value embedded in the product/service offered to the targeted customers (Chesbrough, 2010).
[14] The value capture describes the mechanism of generating incoming revenue flows from the value offered to customers (Dubosson-Torbay et al., 2002).

In light of the overall expectations, incumbents' business models are envisioned to become open and customer-centric and to include interwoven products and services (product-service systems) that are brought to customers in decentralized, local settings. The **role of LSPs** is special, and the expectations for them differ from other incumbents since their traditional business directly depends on the reactions of their customers to AM. Since the 1980s, the growth of the logistics industry has been fueled by globalization and the resulting increased demand for logistics services (Eyers et al., 2019). Paired with the trend of outsourcing, manufacturing firms and retailers have started to vastly outsource their logistics function (Langley et al., 2021; Zacharia et al., 2011). By outsourcing to independent LSPs, manufacturing firms and retailers can achieve cost, quality, and flexibility advantages and concentrate on their core competencies (Andersson & Norrman, 2002; van Laarhoven et al., 2000). LSPs offer a wide spectrum of services, ranging from basic and standardized logistics services to value-added, integrative, and customized services (Carbone & Stone, 2005; Zacharia et al., 2011). Their core business, however, is focused on managing, controlling, and carrying out logistics activities such as the transportation, warehousing, and handling of products on behalf of their customers (Selviaridis & Spring, 2007; van Laarhoven et al., 2000). With manufacturing firms and retailers integrating AM into their business models, they are said to be "freed from many of the logistical requirements of standard manufacturing" (D'Aveni, 2015, p. 47). Most pronounced, decentralized AM close to or at the point of demand is expected to reduce their demand for traditional transportation and warehousing services (Barz et al., 2016a; Eyers & Potter, 2015; Wieczorek, 2017). For example, AM provides manufacturing firms with an alternative for their spare parts business, substituting traditional logistics services (e.g., centralized warehousing of spare parts and transportation to the customer when demanded). Manufacturing firms hence have a new choice in AM, basically "Stock or Print?" (Song & Zhang, 2020). As a result, Savolainen and Collan (2020b, p. 118) predict far-reaching effects of AM on the logistics industry by stating, "All in all what one can observe is that the potential for large changes touches the logistics of manufacturing, including what is being shipped, stored, and the origin and destination of the traffic." These threats that come with AM are expected to force LSPs to react (Chen, 2017).

Generally speaking, the logistics market is known for its high competitive pressure (Hoi Yan Yeung et al., 2006). As basic logistics services are quite simple and standardized, many LSPs are available and, thus, forced to attract their customers with low prices to ensure high utilization of their transportation and warehousing capacities (Andersson & Norrman, 2002). For this reason, it is a well-established thought that LSPs need to be highly adaptable to their customers' requirements and continuously strive for service innovations in the competitive market (Flint et al., 2005). Hence, LSPs are currently under pressure to advance in their digital transformation and exploit new technologies (Cichosz et al., 2020). For example, customer demand for increasingly digitalized services and transparency (e.g., EDI services and order, shipment, and inventory tracking) has required LSPs to build up IT capabilities. With AM and other digital technologies (e.g., autonomous vehicles) rendering logistics services obsolete, LSPs must find ways to innovate and move their existing business models into the digital age (Hofmann & Osterwalder, 2017).

Overall, this section has established an understanding of how AM drives changes in incumbents' business models by encouraging different ways of value creation, embedding value differently in customer offers, and emphasizing different aspects of a revenue model. In addition, this section has underlined the special role of LSPs. It has created awareness for the "dilemma" of LSPs' core business being directly dependent on their customers' reactions to AM. Next, the current state of the literature on AM business models will be discussed with a focus on the positioning of LSPs.

### 2.2.4 Overview of the literature on the additive manufacturing business model development of logistics service providers

This section aims to provide an overview and characterize AM business model research with a focus on LSPs that are confronted with AM. The studies considered in this section, as well as in the entire thesis, result from the constant monitoring of current publications in the business model literature concerning AM. AM business model research is a young research stream. Its initiation – more than 20 years after the development of the first commercially available AM technologies – coincides with the peak of the consumer 3D printing hype in 2013/2014 (see Section 2.1.1). Fundamental work has been conducted by Rayna and Striukova (2016b) and Bogers et al. (2016), whose studies deal with the overall impact of AM on business models. Moreover, systematic literature reviews by Öberg et al. (2018) and by Savolainen and Collan (2020a) provide classifications of the AM business model literature. However, so far, limited research exists for the AM business model development of specific actors. For example, with respect to incumbents, Öberg et al. (2018, p. 21) propose, as part of their research agenda, the need to investigate "how individual firms based on their present roles as manufacturers/suppliers, logistics service providers, and business customers would change or need to change their roles in order to fit with additive manufacturing."

To provide more concrete insights into the current state of AM business model research, Table 2-4 and Table 2-5 structure representative studies. It is noteworthy that several studies take holistic, non-actor-specific perspectives on AM business models. These studies are classified as overviews or by their focus on a SC perspective or AM business ecosystem perspective in Table 2-4. **Overviews** typically deal with the question of how AM impacts existing business models and leads to the emergence of new business models. These studies are commonly based on reviews of the current state of AM business model literature (e.g., Öberg et al., 2018; Savolainen & Collan, 2020a) or are conceptually derived (e.g., D'Aveni, 2015; Despeisse et al., 2017a; Godina et al., 2020; Rayna & Striukova, 2016b). They typically propose future development paths for AM business models (e.g., Savolainen & Collan, 2020a) and research agendas (e.g., Despeisse et al., 2017a). Studies within the **SC** category address AM business models as a cornerstone of how AM affects and changes SCs (e.g., Durach et al., 2017b; Eyers & Potter, 2015). Moreover, the **AM business ecosystem** subsumes studies that track the evolution of the business ecosystem for industrial AM (e.g., Beltagui et al., 2020), partly in combination with the personal 3D printing ecosystem (e.g., Bechtold, 2016). The dynamics of cooperation and competition within the AM business ecosystem evolve as a central topic of these studies (e.g., Cui et al., 2019; Cui & Taohua-Ouyang, 2018; Kapetaniou et al., 2018; Sandström, 2016).

Table 2-4: Thematic categorization of overarching studies on AM business models.

| Category | Representative studies |
|---|---|
| Overviews | D'Aveni (2015); Despeisse et al. (2017a); Despeisse et al. (2017b); Godina et al. (2020); Jiang et al. (2017); Montes (2016); Öberg (2019); Öberg et al. (2018); Rayna and Striukova (2016a, 2016b); Rogers et al. (2018); Savolainen and Collan (2020a, 2020b); Troxler and van Woensel (2016) |
| SC | Ben-Ner and Siemsen (2017); Chan et al. (2018); Durach et al. (2017b); Eyers and Potter (2015); Hasan et al. (2013); Öberg (2022) |
| AM business ecosystem | Bechtold (2016); Beltagui et al. (2020); Cui et al. (2019); Cui and Taohua-Ouyang (2018); Kapetaniou et al. (2018); Li et al. (2017a); Lin et al. (2018); Piller et al. (2015); Ren et al. (2018); Rong et al. (2020); Rong et al. (2018); Rosli et al. (2017); Sandström (2016); Xu et al. (2018) |

In contrast to the overarching studies in Table 2-4, Table 2-5 shows studies that assume actor-specific perspectives within the AM business ecosystem. For **new entrants** from the AM domain, the literature investigating the business models of AM service bureaus and online AM platform providers is comparatively rich, while limited research has so far been conducted on the business models of AM equipment providers. Only Holzmann et al. (2020a, p. 1291) focus on AM machine manufacturers to derive two distinct business models, the "low-cost online model" and the "technology expert model." Previous work on AM service bureaus develops classifications of their distinct service routes (Rogers et al., 2016), offered auxiliary services (Chaudhuri et al., 2019; Chaudhuri et al., 2017), and business models (Holzmann et al., 2020b). Some studies take an even narrower focus on specific services, for example, on design (Cautela et al., 2014) and consulting services (Bugdahn et al., 2019). Studies that investigate the business models of online AM platform providers are equally broad but more end-consumer oriented (Kwak et al., 2018; Rayna et al., 2015). Moreover, it is striking that the combination of AM and cloud manufacturing has become a "new hotspot" in research (Guo & Qiu, 2018, p. 1930), for example, to increase the utilization of AM machines by enabling collaborative access to AM manufacturing resources (e.g., Baumann et al., 2016; Ren et al., 2016). Among the studies investigating the business models of **incumbents** (see Table 2-5), the focus is placed on the positioning of manufacturing firms, retailers, and LSPs in AM. Studies on retailers provide comparable specific mathematical/game-theoretical models for different variants of leveraging AM in retail stores: single and dual sourcing, different ownership models of AM machines, manufacturing semi-finished goods and postponement of the final production step to the retail store, in-store/online sales, and governmental subsidy (Arbabian, 2022; Arbabian & Wagner, 2020; Chen et al., 2021; Jia et al., 2016). Finally, it is noteworthy that some studies span across new entrants and incumbents to place their focus in terms of firm size and age on user entrepreneurs and new ventures. They investigate AM business models for SMEs from the manufacturing domain (e.g., Costache et al., 2021; Flammini et al., 2017; Laplume et al., 2016), startups from the AM domain (Hahn et al., 2014), and user entrepreneurs (Holzmann et al., 2017). In particular, they explore how entrepreneurs and new ventures can benefit from AM. Manufacturing small volumes without heavy investments in tools can enable a positive cash flow for new ventures and a more linear growth than tool-based traditional manufacturing technologies (Rayna & Striukova, 2021).

Table 2-5: Thematic categorization of actor-specific studies on AM business models.

| Category | Sub-category | Representative studies |
|---|---|---|
| New entrants | AM machine manufacturers | Holzmann et al. (2020a) |
| | AM service bureaus | Bugdahn et al. (2019); Cautela et al. (2014); Chaudhuri et al. (2019); Chaudhuri et al. (2017); Holzmann et al. (2020b); Rogers et al. (2016, 2017) |
| | Online AM platform providers | Kwak et al. (2018); Rayna and Striukova (2016c); Rayna et al. (2015)<br>**Cloud-based:** Baumann et al. (2016); Baumann and Roller (2017); Cheng et al. (2018); Guo and Qiu (2018); Qian et al. (2019); Ren et al. (2016); Wang et al. (2019)<br>**Blockchain:** Klöckner et al. (2020); Kurpjuweit et al. (2021); Vatankhah Barenji et al. (2020) |
| Incumbents | Manufacturing firms | Bogers et al. (2016); Cardeal et al. (2020); Chen (2017); D'Aveni (2018); Glas et al. (2021); González-Varona et al. (2020) |
| | Retailers | Arbabian (2022); Arbabian and Wagner (2020); Chen et al. (2021); Jia et al. (2016) |
| | LSPs | Barz et al. (2016a, 2016b); Boon and van Wee (2018); Chen (2017); Cichosz (2018); de la Peña Zarzuelo et al. (2020); Dong et al. (2021); Eyers et al. (2019); Hecker (2021); Hofmann and Osterwalder (2017); Holmström and Partanen (2014); Lahy et al. (2018); Manners-Bell and Lyon (2012); Marek et al. (2020); McKinnon (2016); Pause and Marek (2019); Purvis et al. (2021); Rehnberg and Ponte (2018); Wieczorek (2017) |
| New entrants/ incumbents | Entrepreneurs/ new ventures | Costache et al. (2021); Flammini et al. (2017); Hahn et al. (2014); Holzmann et al. (2017); Laplume et al. (2016); Rayna and Striukova (2021) |

When taking a closer look at **LSPs**, it becomes evident that the understanding of the effects of AM on their core business models is so far insufficient. Similar observations have been made in the literature: Barz et al. (2016a, 2016b) notice that previous work hardly quantifies the impact of AM on logistics, while Dong et al. (2021) state that there is a lack of empirical validation. Moreover, Boon and van Wee (2018) subsume that experts' options are divergent and that many direct and indirect effects of AM raise uncertainty when it comes to the impact of AM on transportation and associated costs. For example, decentralized AM reduces the need for long transportation (e.g., for spare parts) but offers only limited options for pooling volumes for the last mile, which reduces the cost efficiency. Similarly, AM simplifies raw material logistics, but decentralized AM requires stocks of raw materials at each location. Despite such ambiguous effects and the lack of quantification, literature-based **expectations for the influence of AM** on logistics can be extracted from the studies in Table 2-4 and Table 2-5, as summarized in Table 2-6. The expectations point to an overall decreasing demand for logistics services. Most pronounced are arguments based on the AM-initiated business model transformation of manufacturing firms as LSPs' typical customers. As visible in Table 2-6, several studies refer to a shift from centralized to decentralized AM to reason on the influence of AM on logistics services. In addition, previous studies base their arguments on the nature of AM (e.g., its higher resource efficiency, see Section 2.1.3) and the global trend of reshoring. Described as the relocation of manufacturing activities from low-cost countries back to high-cost countries in Europe and the US (Laplume et al., 2016), reshoring is expected to lead to a decrease in global transportation, particularly sea and air freight, and the emergence of smaller and denser transportation networks that promote road and rail freight transportation.

Table 2-6: Structuring of the influences of AM on logistics services.

| Category | Influence of AM on logistics services | Representative studies |
|---|---|---|
| Business model transformation of manufacturing firms | **Centralized → Decentralized:** Reduction of inventory by on-demand decentralized manufacturing; reduction of transportation volumes/ton kilometers by digitally transferring the digital product specification to a manufacturing location close to or even to the point of demand; less handling and packaging | Arbabian and Wagner (2020); Barz et al. (2016a, 2016b); Ben-Ner and Siemsen (2017); Cardeal et al. (2020); D'Aveni (2015); Despeisse et al. (2017a); Eyers and Potter (2015); Holmström and Partanen (2014); Klöckner et al. (2020); Kurpjuweit et al. (2021); Laplume et al. (2016); Marek et al. (2020); Montes (2016); Öberg (2019, 2022); Rayna and Striukova (2021); Rogers et al. (2016) |
| | **Close → Open:** Increasing delegation of services to industrial customers (self-services) and end consumers (home fabrication) to further reduce the need for logistics services; reduced inventories for mass-customized products | Manners-Bell and Lyon (2012); Öberg (2019); Troxler and van Woensel (2016) |
| Nature of AM | AM increases the **resource efficiency**; AM has a better "buy-to-fly" ratio than traditional manufacturing technologies; smaller quantities of raw materials need to be stored and transported; effect depends on the recycling rate of AM materials | Barz et al. (2016a, 2016b); Chen (2017); Wieczorek (2017) |
| Global trend of reshoring | **Relocation of manufacturing activities** from low-cost countries to Europe and the US; reduction of demand for international transportation; saving of import tariffs and bypassing of technical barriers | Chen (2017); Durach et al. (2017b); Laplume et al. (2016); Manners-Bell and Lyon (2012) |
| | **Country-specific impact** of reshoring; depends on the role as a resource country, producer country, or consumer country in AM | Chen (2017) |
| | **Less medium- und long-distance transportation** (e.g., air and sea freight); smaller and denser transportation networks (e.g., road and rail freight) | Boon and van Wee (2018) |

Moreover, the extant literature provides insights into the **expectations for the remaining need for logistics services** for AM, as summarized in Table 2-7. Identified expectations point to an increasing emphasis on logistics services for raw materials and the last mile for AM end products, whereas the relevance of logistics services for semi-finished products may decrease. The underlying argumentation is based on the ability to manufacture AM parts (e.g., spare parts) in one run (Laplume et al., 2016; Manners-Bell & Lyon, 2012).

In summary, previous work fosters the impression that AM has the potential to substitute or simplify traditional logistics services (e.g., Cichosz, 2018; Godina et al., 2020; Jia et al., 2016; Jiang et al., 2017). AM technologies are expected to put LSPs in a vulnerable position where their services can become redundant (Öberg, 2022). However, based on the limitation of AM to specific applications (see Section 2.1.4), a partial substitution is currently observable and the realistic spectrum is rather unclear (Hofmann & Osterwalder, 2017). For example, Chen (2017) imagines the wide span of 7% to 60% of the global containerized freight volume to be affected by AM depending on whether new AM application fields (e.g., electronics) are tapped. Technological advances can potentially increase the substitution and the threat of AM for LSPs (Cichosz, 2018). Nevertheless, concerns are raised that, even in the long term, AM and its decentralization will not be a suitable strategy for all kind of products (e.g., for mass-produced parts), so substitution remains limited in many cases (Jiang et al., 2017; Savolainen & Collan, 2020b).

Table 2-7: Structuring of the remaining logistics services for AM.

| Category | Remaining logistics services for AM | Representative studies |
|---|---|---|
| AM simplifies logistics services for **raw materials**, but decentral AM creates additional raw material inventories | Low variety of input materials for AM; raw materials for AM can be aggregated and supplied via bulk transportation with minimal packaging | Ben-Ner and Siemsen (2017); Boon and van Wee (2018); Durach et al. (2017b); McKinnon (2016); Ren et al. (2018) |
| | AM material manufacturers are still rare and geographically concentrated, which creates additional transportation | Despeisse et al. (2017a); González-Varona et al. (2020) |
| | Decentral AM creates additional inventories of raw materials at each decentral location | Durach et al. (2017b) |
| AM reduces logistics services for **semi-finished goods** | Elimination of the assembly phase; removal of storage, handling, and distribution costs involved in bringing together the relevant components | Manners-Bell and Lyon (2012) |
| AM emphasizes **last-mile logistics** services, but pooling transportation is limited in decentral settings | AM distribution networks must be organized efficiently (e.g., reduction of the number of empty vehicles; more nodes and more flexibility) | Boon and van Wee (2018) |
| | Reduced options for pooling transportation volumes in decentral settings | Durach et al. (2017b); Eyers and Potter (2015) |

Even though the effects of AM on the demand for logistics services are not fully understood yet, the **need for LSPs to react** proactively to AM is pronounced in the AM business model literature (e.g., Chen, 2017; Öberg, 2022). For example, Hecker (2021, p. 437) goes as far as terming the importance of AM for LSPs to be "uncontroversial," and Manners-Bell and Lyon (2012) call for the need for a new logistics firm in the era of AM. In this vein, LSPs are not expected to accept the threats of AM but to transform them into opportunities and renew themselves by establishing new business models for AM (Manners-Bell & Lyon, 2012). The idea behind this thought is that LSPs can develop AM-specific business models to balance the losses in their traditional business. In doing so, they can continue to serve their existing customers while trying to establish a new competitive position for themselves in the AM business ecosystem (Öberg, 2019, 2022). However, so far, research on AM business models for LSPs and service providers in general is limited (Eyers et al., 2019). In this sense, Pause and Marek (2019, p. 57) propose the need for an in-depth exploration of AM business models for LSPs by stating, “business models have to be identified in order to quantify the value created for the LSP and enable a well-founded decision to be made.” Furthermore, in the broader context, there is a need to address the digital disruptions in the logistics industry resulting from AM and other digital technologies (e.g., robotics, automated vehicles, and drones) (Hofmann & Osterwalder, 2017).

So far, several studies, in particular, the ones that provide direct insights into the positioning of LSPs in the AM business ecosystem in Table 2-5, propose conceptually derived **visions of “finished” AM business models**. The obvious vision of LSPs as manufacturers for AM is specifically widespread. Several studies suggest that this vision can be realized by implementing AM in LSPs’ existing decentral warehouses and distribution centers (e.g., Durach et al., 2017b; Rehnberg & Ponte, 2018; Wieczorek, 2017). Analog to retailers, the underlying arguments for the positioning of LSPs as manufacturers in AM are based on the low skill requirements for the AM process (Ben-Ner & Siemsen, 2017). Via cooperation with manufacturing firms, the final manufacturing step could be postponed and performed by LSPs (Holmström & Partanen, 2014; Purvis et al., 2021; Wieczorek, 2017). Such expectations show that the trend of manufacturing decentralization is recognized as an opportunity for service growth for LSPs. Lahy et al. (2018), Eyers et al. (2019), and Purvis et al. (2021) complement this vision with case-based evidences of why AM lowers the barriers of LSPs to follow a “productization” strategy of combining AM with their traditional services. Additional visions for the positioning of LSPs in AM exist, for instance, as developers of safe digital infrastructure (Holmström & Partanen, 2014) and in their traditional role as LSPs (Rogers et al., 2016). Figure 2-6 provides an overview of the identified visions of AM business models for LSPs from the studies considered in Table 2-4 and Table 2-5.

LSPs as manufacturers

- LSPs place AM machines in **warehouses or distribution centers** for manufacturing postponement (Durach et al., 2017b; Eyers et al., 2019; Hofmann & Osterwalder, 2017; Lahy et al., 2018; Pause & Marek, 2019; Rehnberg & Ponte, 2018; Purvis et al., 2021; Wieczorek, 2017)
- LSPs place AM machines at **strategic nodes** like airports (D’Aveni, 2018) or ports (de la Peña Zarzuelo et al., 2020)
- LSPs operate **local print hubs/“printing houses”** close to end customers for increasing the utilization of AM machines while reducing the need for transportation (Boon & van Wee, 2018; McKinnon, 2016; Öberg, 2019, 2022)
- LSPs place AM machines in **moving trucks** to reduce the lead time by manufacturing while delivering the parts to customers (Hofmann & Osterwalder, 2017; Manners-Bell & Lyon, 2012)

LSPs as developers of digital infrastructure

- LSPs act as **trusted handlers/gatekeepers of digital product specifications**; LSPs develop digital infrastructure and secure access to digitally encapsulated AM design files (Holmström & Partanen, 2014; Pause & Marek, 2019)
- LSPs act as **software providers** for AM feasibility assessment, AM service bureau selection, as well as data management and authentication (Marek et al., 2020)

LSPs as providers of traditional logistics services

- LSPs offer transportation and warehousing of **raw materials** for AM (Ben-Ner & Siemsen, 2017; Cichosz, 2018; Manners-Bell & Lyon, 2012; Wieczorek, 2017)
- LSPs offer efficient logistics solutions for the **last mile**, for example, for transporting finished AM parts from AM service bureaus to their customers (Guo & Qiu, 2018; Holmström & Partanen, 2014; Pause & Marek, 2019; Ren et al., 2016; Rogers et al., 2016; Wieczorek, 2017)

LSPs as consultants/service managers

- LSPs offer decision support for the **selection of manufacturing technologies** (AM versus traditional manufacturing technologies) (Pause & Marek, 2019)
- LSPs offer support for **the selection of AM service bureaus** that fit specific orders (Pause & Marek, 2019)
- LSPs as **management service providers** that offer brainpower-based services throughout the product life cycle, for example, a mix of software development, delivery services, partner relationship management, and contract management (Manners-Bell & Lyon, 2012)

Figure 2-6: Visions of AM business models for LSPs.

By applying an **output perspective**, the provided visions are static and do not sufficiently consider how LSPs currently react to AM with specific AM activities and if their currently selected paths actually lead them toward the envisioned positions. So far, approaches in the literature neglect that LSPs transform and adapt their business models in an ongoing, potentially cyclic process as described in Section 2.2.1. For example, several LSPs that traditionally provide standard logistics services have started to use AM in-house to increase the availability of spare parts in their maintenance, repair, and operations (MRO) departments (e.g., ÖBB (Spiess, 2020) and the Port of Rotterdam (Port of Rotterdam, 2019)). Other LSPs are currently in the process of observing AM, generating AM-specific services, testing, and running these business models (e.g., Royal Mail (Molitch-Hou, 2014) and La Poste (O'Neal, 2015)). Hence, there is a need for a process-based perspective on LSPs' current responses to AM. For instance, Flammini et al. (2017) find evidence that manufacturing firms tend to choose familiar business models in the face of high uncertainty (as created by AM). In doing so, they propose that manufacturing firms do not even need to make radical changes but can develop interim strategies and deliberately adapt their business models to AM. In addition, their study indicates that manufacturing firms can establish multiple coexisting business models in parallel (e.g., for AM and traditional manufacturing). The same may be true for LSPs since they are equipped with their traditional logistics resources (e.g., transportation fleets and warehouses) and competencies. Hence, the interaction and compatibility of AM activities and their existing business models is important. Hecker (2021) makes a step into this direction by proposing that developed AM services should complement LSPs' existing service portfolio. Hecker (2021) creates awareness that LSPs lack specific skills and competencies for AM by raising the question of which competencies should be developed in-house, purchased from suppliers, or internalized via acquisitions by LSPs. Moreover, it is essential to understand how ambitiously LSPs approach AM and if their initiatives (e.g., to become manufacturers in AM) remain a "quite experimental idea that in the end might not even have a time lapse to fill," as feared by Öberg (2022, p. 323). Hence, there is a need for studies that shift from the output perspective to assume a process-based perspective, which enables them to investigate the "small steps" of how and why incumbents respond to AM with a business model lens. This **research gap** is addressed for LSPs with the overarching research question RQA in part A of this thesis. Currently observable AM activities of LSPs and their interaction with LSPs' traditional business models are explored. On this basis, empirically grounded business model configurations for LSPs are developed.

## 2.3 Supply chain design for additive manufacturing

As new actors enter the AM market with new business models and incumbents are in the process of adapting and innovating their traditional business models to leverage the potential of AM, their SCs need to be designed to accommodate AM. In particular, moving AM downstream and decentralizing it for small-scale production close to or even at the point of demand is expected to revolutionize the traditional SCD (Ghobadian et al., 2020). In analogy to the motivated AM business model development in Section 2.2, this section sets the ground for investigating the impact of AM on the traditional design of SCs and provides an overview of previous research dealing with the AM SCD choice. First, Section 2.3.1 introduces the OSCM perspective on strategic SCD decisions. Then, Section 2.3.2 builds an understanding for the traditional SCD in order to derive the impetus of AM for SC (re-)design in Section 2.3.3. The section closes with an overview of the current state of the OSCM literature on the AM SCD choice of manufacturing firms in Section 2.3.4.

### 2.3.1 The perspective of operations and supply chain management research

The understanding that firms do not compete as autonomous entities but are integrated into networks of business relationships has shaped the discipline of supply chain management (SCM) (Lambert et al., 1998). A **SC** "encompasses all organizations and activities associated with the flow and transformation of goods from the raw materials stage, through to the end user, as well as the associated information flows" (Handfield & Nichols, 2002, p. 8). Other definitions, for example, proposed by Mentzer et al. (2001), concretize the flows by establishing that SCs involve upstream and downstream flows of products, services, finances, and information. Furthermore, it is emphasized in the SCM literature that "networks" are more suitable to describe the structure of SCs since firms commonly have multiple suppliers, suppliers' suppliers, and analogously multiple customers and customers' customers (e.g., Christopher & Holweg, 2011; Cohen & Lee, 1988; Lambert & Cooper, 2000). SCs vary in their complexity, ranging from a direct SC of three parties to an ultimate SC that considers all links between all actors involved (Mentzer et al., 2001). To manage this complexity and maintain a focus, several SCM studies take a firm- and industry-centric view (e.g., Demeter et al., 2006; Roh et al., 2011). Thus, studies commonly focus on the perspective of a focal firm, which is structurally located in the center of the SC. The focal firm maintains relationships with suppliers in its upstream SC and with customers in its downstream SC (Choi & Krause, 2006). The focal firm is understood as the essential actor that governs, coordinates, and controls the SC to a large degree (Handfield & Nichols, 1999). By taking a focal-firm orientation, tiers without direct connections to the focal firm, for instance, third- and fourth-tier suppliers, may not be considered in investigations.[15] Note that the term "tier" describes the number of sequential firms in a SC that perform the transactions which lead to the final customer (Gardner & Cooper, 2003). The resulting architecture of a focal firm SC is visualized in Figure 2-7. This thesis follows previous studies by taking a focal firm perspective of manufacturing firms (component and end-product manufacturers) on SCs coupled with an industry-centric view on emerging industrial AM.

The **concept of SCM**, as initially introduced in 1982 by two consultants, refers to the management of relationships within SCs with the objective of enhancing the overall performance (Halldorsson et al., 2007). It focuses on the strategic coordination and integration of business functions within firms and across the firms within a SC. Thus, SCM is a systems approach that views the SC as a whole (Min & Mentzer, 2004). Traditional firm functions such as marketing, sales, research and development, forecasting, procurement, production, and logistics are included in the scope of SCM (Mentzer et al., 2001). Such an extension of the thought of functional integration from the firm level to SCs requires a long-term orientation and shared vision among the SC actors. Moreover, it necessitates the firms' focus on cooperation, trust, and a high level of information sharing (Cooper & Ellram, 1993; Handfield & Nichols, 2002; Lambert et al., 1998). As a further characteristic, SCM is coined as a customer-focused concept. It aims to achieve performance improvements by synchronizing and converging the whole SC. Desired performance improvements are realized with cost reductions or with superior value delivered to the final customer (Christopher & Holweg, 2011). The desired customer satisfaction, in turn, enhances the competitive advantage and ultimately increases the profitability of a SC and its involved firms (Mentzer et al., 2001).

SCM is considered to be strategic by nature (Min et al., 2019). Despite this, SCM is affected by firms' planning decisions on all management levels (Ivanov, 2010). The literature, therefore, commonly differentiates between **three SCM planning levels**, the strategic, tactical, and operational planning (Talluri, 2000). Operational decisions are short-term and focused on day-to-day activities of the running SC. They include, for example, operative order planning, monitoring of the SC, and the management of operative disruptions. Tactical planning considers a longer time horizon of weeks or months and deals with planning problems such as demand forecasting, master production planning, supply planning, replenishment planning, inventory management, and transportation planning (Ivanov, 2010; Mele et al., 2007). Strategic SC decisions have a long-term horizon of five to ten years and aim at determining the SCD (Beamon, 1998; Gupta & Maranas, 2003). In this context, the SCD describes strategic decisions that define the physical structure and infrastructure of SCs (Govindan et al., 2017). Commonly, SCD decisions deal with the selection and development of suppliers and sourcing strategies, the number and location of facilities (e.g., for production, storage, distribution, retail, etc.), the capacity of each facility, distribution strategies, and the se-

[15] Lambert and Cooper (2000) find that SCs vary from each firm's perspective, since each management sees its firm in a focal position and has a different perspective on the SC actors involved.

lection of transportation modes (Chandra & Grabis, 2007; Kouvelis et al., 2006). Hence, defining the SCD includes multi-level decisions that require integration with the product/service and process design (Kouvelis et al., 2006). Fine (2000, p. 213) assesses the SCD decision as "the ultimate core competency of an organization" and narrows it down to how a focal firm, termed the "dominant producer" by Fine (2000, p. 215), sets the boundaries of its firm. For example, Fine (2000) describes for the computer industry how a single product decision of IBM as a response to the emergence of the Apple Computer triggered a structural shift of the SC and overall industry. IBM's modularization of the product architecture fostered the market entry of multiple suppliers for subcomponents, which turned the overall SC from a vertically integrated into an outsourced/disintegrated version with fierce competition. With emerging sub-industries (e.g., the semiconductor industry), the horizontal scope of SCs also changed. On this basis, a SCD can be suitably characterized by its horizontal and vertical scope. Both structural dimensions are illustrated in Figure 2-7. They are established in the OSCM literature but referred to with slightly different terminologies. For example, Lambert et al. (1998) differ between the horizontal and vertical structure of a SC, while Chandra and Grabis (2007) distinguish between the horizontal and vertical extent. Notably, Choi and Hong (2002) interpret the two dimensions differently.

In this thesis, the **horizontal scope** of a SC refers to the number of tiers across a SC, following Lambert et al. (1998). Each tier represents organizational entities with the general same functionality (Chandra & Grabis, 2007), see Figure 2-7. Thereby, the horizontal scope defines the length of a SC and has geographic implications. In this context, the *geographic dispersion* of a SC refers to the extent to which its entities span across geographic regions based on the locations of the involved actors, for example, suppliers, production facilities, distributors, and customers (Handley & Benton, 2013). It thus influences how activities are distributed in a SC, and it affects the allocation of the decision-making authorities. Specifically, the geographic dispersion provides insights into the location of manufacturing plants in the SC (Stock et al., 2000). With such a direct focus on the location of manufacturing plants, Kotha and Orne (1989, p. 222) and Shi and Gregory (1998, p. 203) use the terms "geographic manufacturing scope" and "degree of plants dispersion" similarly to geographic dispersion. They describe different levels of geographic expansion, from domestic to regional, national, multinational, and global/worldwide manufacturing plants. Applying their understanding to SCs suggests that a distinction can be made between whether a SC is centralized or decentralized. A centralized SC is a concentrated SC with a low geographic dispersion, while a decentralized SC covers geographically dispersed locations and consequently has a high geographic dispersion (Stock et al., 2000).

The **vertical scope** of a SC refers in this thesis to the number of firms (e.g., suppliers, manufacturing firms, etc.) that are present at each tier (Lambert et al., 1998). Similarly, Stock et al. (2000, p. 534) refer to vertical integration to describe the "extent to which the firm owns the stages of the supply chain from raw materials to distribution." What Stock et al. (2000) paraphrase in this definition is the differentiation between a vertically integrated SC and a specialized, outsourced SC, as also contrasted by Tsay et al. (2018). Differences in the vertical scope of SCs result from the governance choice of firms on the spectrum from hierarchy to market. Hierarchy (i.e., in-house or "insourced" activities) and the free market (i.e., outsourced activities) characterize the two polar governance structures that firms can select for their transactions. They are the outcomes of firms' make-or-buy decisions (Williamson, 1975). Vertically integrated SCs emerge when firms opt for in-house activities and, for instance, perform all the manufacturing activities to transform raw materials into the final product themselves. On the contrary, specialized SCs with a low vertical integration emerge when firms outsource various functions and, for example, only perform the final assembly of end products in-house (Kotha & Orne, 1989; Stock et al., 2000).

Both dimensions are considered in this thesis to characterize the design of SCs. It is an underlying assumption of this thesis that focal manufacturing firms as "dominant producers" determine the horizontal and vertical scope of SCs to a large extent. Their choices of geographic dispersion define the location of manufacturing activities and related activities in the SC (central versus decentral) and, thus, target the question of *where* the manufacturing activities take place in the SC. Similarly, their make-or-buy decisions for manufacturing activities and related activities define the governance structure of the SC (market/outsourcing versus hierarchy/in-house) and, hence, address the question of *who* manufactures in the SC.

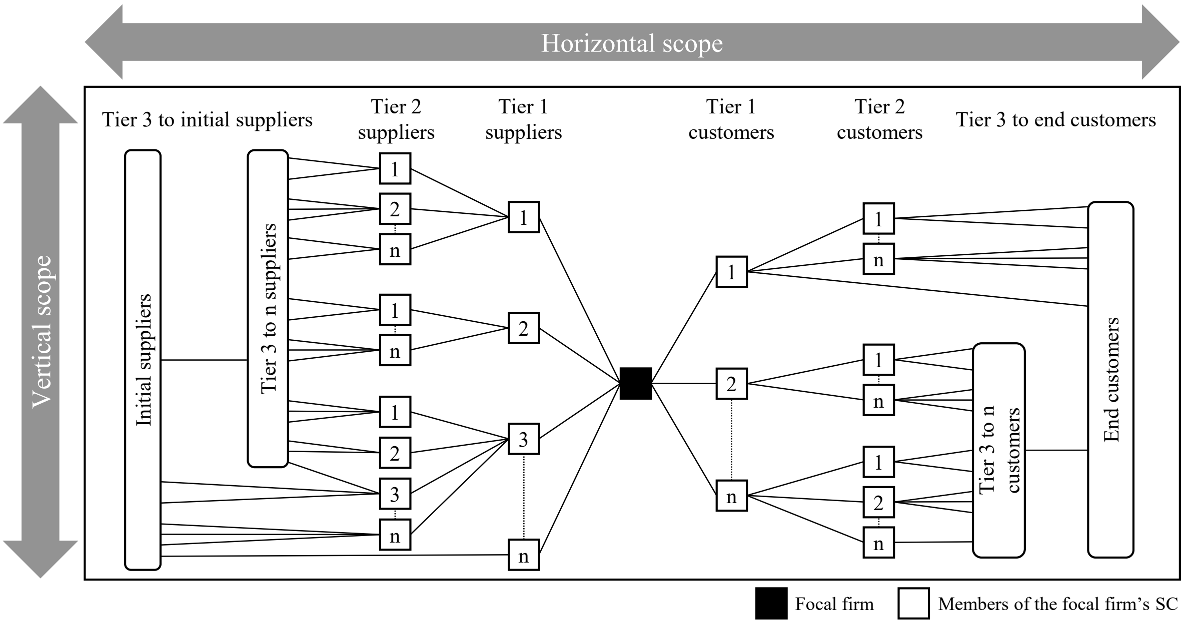



Figure 2-7: Focal-firm SC (based on Lambert et al. (1998, p. 3)).

Finally, it should be noted that SCM and the involved strategic SCD choice is not a static task. Rapidly changing markets, volatilities in the business environment, and shifts in customer expectations challenge the long-term competitiveness and survival of SCs (Gupta & Maranas, 2003). Generally speaking, the idea that firms adjust their **SCs as "configurable systems"** to their changing environment has been established for years, as outlined by Chandra and Grabis (2007). Since Fisher's (1997) question, "What is the right supply chain for your product?", the match of products, primarily consumer products, with SCs has attracted the attention of researchers. Fisher (1997) distinguishes between functional products that need efficient SCs and innovative products with a need for responsive SCs. Several studies have followed, proposing that the SCD should be aligned with specific product characteristics (e.g., product type, product volume, stage in the product life cycle), demand characteristics (e.g., predictability, demand uncertainty), and supply characteristics (e.g., supply uncertainty) (Christopher, 2000; Lee, 2002; Mason-Jones et al., 2000; Naylor et al., 1999; Reiner & Trcka, 2004; Vonderembse et al., 2006). Furthermore, studies have addressed the benefits of also considering the design of the manufacturing process for designing SCs (e.g., Blackhurst et al., 2005; Singhal & Singhal, 2002). In sum, these studies have established specific configurations of coherent SCD patterns, including lean SCs, agile SCs, the combination of both termed "leagile" SCs, and several other designs (e.g., efficient, responsive, or flexible SCs). Such configurations are recognized as traditional paradigms of SCM. More recently, Christopher and Holweg (2011, p. 80) called for a paradigm shift and the need for structurally flexible SCs that are adaptable to cope with high volatilities in the business environment by emphasizing, "Any competitive advantage is temporary, so it is important to build supply chains that are adaptable to turbulence." AM and other Industry 4.0 technologies may be one cornerstone for fostering the emergence of more flexible and also demand-oriented SCDs (Christopher & Holweg, 2011; Christopher & Ryals, 2014). Lately, based on the disruptive potential of these technologies, the literature has raised high expectations that they will continue to drive digital transformation and cause major changes in SCDs (e.g., Goldsby & Zinn, 2016; Min et al., 2019; Olsen & Tomlin, 2020; Waller & Fawcett, 2014).

As a result of the outlined reasoning, SCs should be considered as being in a **constant flux of change** (Blackhurst et al., 2005). This thought is also established by Choi et al. (2001), who argue for the need to recognize SCs as complex adaptive systems. Following their understanding, SCs evolve in an interplay and process of co-evolution with their environment. In a similar vein, Piramuthu (2005) advises managers to dynamically configure SCs as required by changes in their competitive environment and proposes an automated framework to configure SCs for this purpose. With that, Piramuthu (2005, p. 220) fosters the understanding that SCD is not a "one-shot problem" but a constant effort of reconfiguration. SCs should be kept flexible for making appropriate changes while sticking to pre-defined goals. Coming back to the two dimensions selected to characterize SCDs in this thesis, the understanding of non-stable SCDs raises the expectation that SCs may move between different forms on the spectrum of their geographic dispersion and governance structure.

This section has established the understanding of a SC as a configurable system that requires constant adaptation. It has further introduced two dimensions that are considered in this thesis to characterize the SCD choice, the horizontal scope (with its geographic implications) and the vertical scope (with its underlying SC governance choice). Moreover, this section has introduced manufacturing firms as "dominant producers" or focal firms that influence the SCD with their choices of geographic dispersion (central versus decentral) and governance structure (in-house versus outsourcing) to a large extent. On this basis, the next section describes the traditional global SCD that has emerged from the trends of offshoring and outsourcing in many industries.

### 2.3.2 The traditional supply chain design

Dating back to the age of the industrial revolution in the 18th and 19th centuries, manufacturing eras have been characterized by **centralized, large-scale operations**. Mass production provided low-cost products based on economies of scale, high standardization, and a high division of labor (Hu, 2013). Large efficiency gains were realized. For example, with a moving assembly line, Ford achieved reductions in the throughput time of a car from 12:08 hours in 1913 to 01:35 hours in 1914. Economies of scale enabled Ford to produce 1,000 cars per day and sell them for lower prices than their competitors (Chandler, 1997). The trend of globalization has further transformed centralized factories into international locations that can serve global markets (Srai et al., 2016b). There has been a significant shift of firms toward offshoring their manufacturing operations stimulated by the reduction of trade barriers, advances in information and communication technologies, and the containerization of freight transportation (Laplume et al., 2016). In this context, offshoring is understood as the choice to locate manufacturing activities and related activities (e.g., research and development and services) outside a firm's home country (Larsen et al., 2013). Between the early 1990s and mid-2000s, firms notably opted for offshoring to developing countries and outsourced their operations to suppliers based on low labor and raw material costs (Ashby, 2016; Tate et al., 2014).

The **trends of offshoring and outsourcing** practices have been pronounced in labor-intensive industries (e.g., furniture, textiles, and apparel) and less in resource-intensive industries (e.g., mining, agriculture, and energy) (McKinsey, 2020). Various studies refer to the paradigm of the "global factory" to describe global manufacturing systems with geographically dispersed production capacities in developing and industrialized countries (Buckley & Strange, 2015; Gereffi, 1989). As a consequence, goods and services have become disaggregated ("fine-sliced") in the SC; they cross national boundaries and change the hands of different parties several times, resulting in an enhanced need for coordination (Buckley & Strange, 2015; Sasson & Johnson, 2016). In combination, both trends of offshoring and outsourcing have resulted in long, global, and complex SCs (horizontal scope) that consist of multiple, highly specialized firms with a low degree of vertical integration (vertical scope). Such SCs are coined as traditional SCs in this thesis. A schematic traditional SCD is visualized and characterized in Figure 2-8. This illustration simplifies the traditional SC to a linear SC from a focal firm perspective of an end-product manufacturer with a centralized manufacturing plant. It ranges from the phase of procurement to manufacturing and distribution, and it simplifies the SC flows to the primary material flows. Thus, Figure 2-8 does not integrate reverse flows (e.g., for recycling, reusing, and repairing) as generated in circular SCs (Farooque et al., 2019). Moreover, it does not visualize the initial material flows required for setting up the SC (e.g., for purchasing machines and equipment and for the construction of factories).

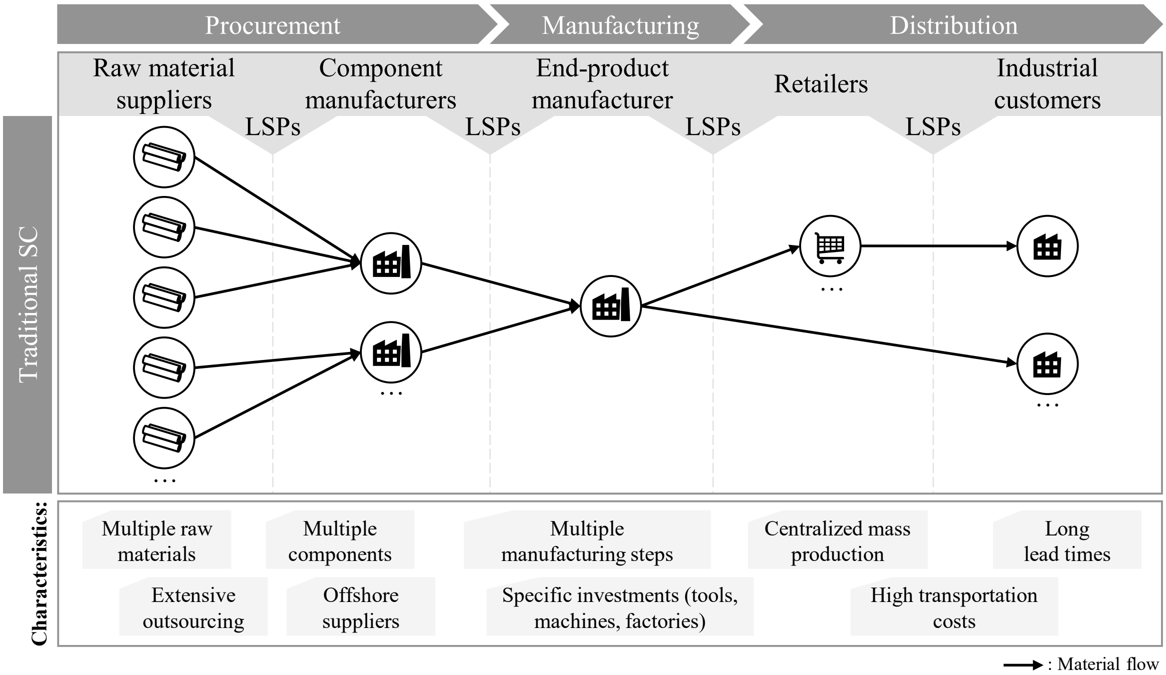



Figure 2-8: Schematic traditional SCD.

In recent years, global SCs have faced increasing **criticism** for their high complexity, length, and low responsiveness (Srai et al., 2016b). The "fine-slicing" contributes to longer, cumulated lead times and temporally separates the demand from the supply. This separation creates uncertainty and inefficiencies that are visible in overproduction, safety stocks, and reduced service quality (Sasson & Johnson, 2016). Moreover, manufacturing far from the point of demand is recognized for its negative impact on the environmental footprint of SCs, mainly based on the required global transportation (Sundarakani et al., 2010). In this vein, Christopher and Holweg (2011, p. 80) point to a shift in the public perception by emphasizing a now obsolete assumption – "the 'low-cost country advantage' generally outweighs the transportation cost in global supply chains no longer holds." In addition, global SCs are increasingly exposed to risks of disruption, as it has been evident in recent global crises (McKinsey, 2020). Given the pressure of reducing the global footprint and the growing need for more resilient SCs in the face of today's volatile business environment, firms have started to revisit their decisions for offshoring combined with outsourcing. According to Tate et al. (2014), the reverse trend of reshoring has been underway since the early 2010s. Besides, other measures have gained recognition for fostering SC resilience. The literature widely discusses practices of redundancy and flexibility to increase SC resilience; see Kamalahmadi and Parast (2016) for a broader introduction to the field. Given the criticism of traditional SCs, the next section will detail how AM is predicted to impact and change manufacturing firms' SCD choice.

### 2.3.3 Impulse given by additive manufacturing for supply chain (re-)design

Based on the advantages of AM (see Section 2.1.3), the emerging digital technologies are expected to challenge the traditional design of SCs and foster the trend of reshoring. Concerning the horizontal scope, AM SCs are expected to become shorter, less complex, and decentralized. For the vertical scope, expectations point to an increase in the outsourcing of manufacturing activities. The following two paragraphs detail these expectations for the horizontal and vertical scope of AM SCs.

**Horizontal scope:** Traditional decision-making based on economies of scale for the manufacturing location does not apply to AM SCs. AM is expected to facilitate a shift from centralized (mass production) to decentralized (small-scale production) SCs (Ghobadian et al., 2020; Olsen & Tomlin, 2020). Individual parts can be manufactured on demand close to or even at the point of consumption, which reduces lead times and is particularly advantageous for uptime-critical spare parts. Key aspects that foster this expectation are the general-purpose characteristics of AM machines (see Section 2.1.3). With ideally only the digital design file and basic raw materials as required inputs for the AM process, the supplier base is significantly reduced to basically one raw material supplier. Raw materials for AM are coined to be unspecific and universally usable (Rylands et al., 2016). They can be easily supplied via bulk transportation (McKinnon, 2016). Based on these characteristics, AM simplifies the raw material procurement process (Mellor et al., 2014). The one-step manufacturing process itself does not require specialized factories. Ideally, no investments in product-dependent assets are required in the AM SC (Verboeket & Krikke, 2019). In addition, less or ideally no waiting times for product-specific resources (e.g., for tools) and other manufacturing activities (e.g., for components), potentially taking place at other locations in the SC, occur (Matt et al., 2014; Mellor et al., 2014). Hence, for stand-alone AM parts, the independence of the manufacturing process increases in the AM SC. Location-independent AM machines can ideally be placed anywhere in the downstream SC, for example, in retail stores and LSPs' warehouses (see Section 2.2.3). Another compelling feature in this regard is the potential to reduce and (ideally even completely) eliminate the manual labor input. Already today, AM requires less and lower-skilled manual intervention of machine operators than for traditional manufacturing (Zijm et al., 2019), see Section 2.1.3. Assuming that manual intervention for the AM process and pre-/post-processing will further decrease, the high automation of AM has the potential to nullify the cost advantage of manufacturing in low-cost countries (Laplume et al., 2016). In summary, the specific characteristics of AM promote a more simplified, shorter, more flexible, and responsive SCD than what is commonly established for traditional manufacturing technologies (Arbabian & Wagner, 2020; Holmström et al., 2010; Verboeket & Krikke, 2019). Min et al. (2019) propose that the industrial AM SC can be reduced to three actors – a focal manufacturing firm, its direct supplier, and its customer. Such a SC shrinks significantly in terms of its geographic dispersion and, hence, its horizontal scope (Sasson & Johnson, 2016). As already established (see Section 2.2.4), this holds the potential to reduce transportation volumes and inventory in the SC and positively affect its environmental performance (McKinnon, 2016; Rylands et al., 2016).

**Vertical scope:** The expectation of increased outsourcing of manufacturing activities to AM service bureaus is mainly based on the digital nature of AM technologies. Digital product specifications can be easily shared, modified, and reused (Berman, 2012). Thus, they can also be seamlessly transferred to AM outsourcing partners in the SC (Hedenstierna et al., 2019; Khajavi et al., 2014). Moreover, as competencies for AM are expected to be easy to acquire, manufacturing firms are not dependent on the AM expertise and skills tied to specific outsourcing partners. AM service bureaus, as the predestined outsourcing partners for AM, become interchangeable, thereby facilitating flexible outsourcing relationships (Zijm et al., 2019). In this vein, Rayna and Striukova (2016b, p. 219) propose, "Instead of one or a few manufacturers, a firm potentially has thousands of manufacturers to work with." By selecting AM service bureaus close to the point of demand, manufacturing firms can make use of the combination of decentralizing and outsourcing AM. In doing so, outsourcing becomes a means to facilitate decentralization and get manufacturing firms increasingly involved in multiple and local sourcing (Meyer et al., 2021). From the perspective of AM service bureaus as outsourcing partners, the investments in general-purpose AM machines are not specific to any customer or product (Scott & Harrison, 2015). Holmström et al. (2016, p. 5) therefore refer to "pools of local (generalized) service providers." By consolidating orders from multiple customers, AM service bureaus are expected to maximize the utilization of the build volume of AM machines and achieve economies of scale at fixed setup costs, for example, for the machine warm-up (Baumers et al., 2016; Öberg, 2019).

Figure 2-9 starts by illustrating a traditional SCD for AM, analog to Figure 2-8. It assumes that the AM machine is centrally located at the end-product manufacturer in the SC who uses AM technologies in the illustrated example to manufacture stand-alone applications in a one-step process (e.g., specific spare parts). In addition to the basic material flows, the transfer of digital product specifications to the AM machine is essential for inherently digital AM technologies. It is thus also included in Figure 2-9.

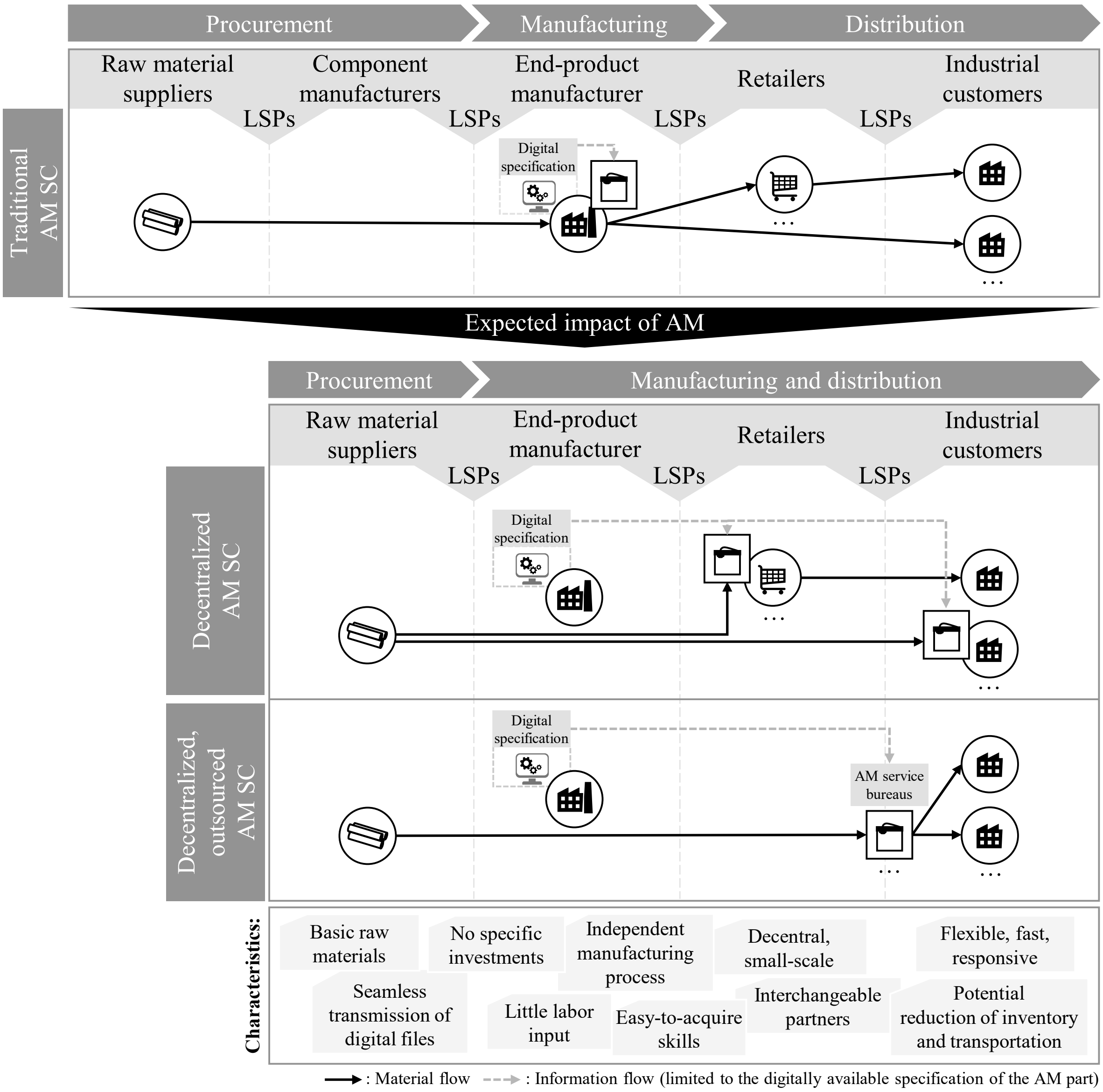



Figure 2-9: Schematic AM SCDs.

Figure 2-9 then schematically illustrates the vision of shorter, decentralized, and less complex AM SCs. The centrally manufactured spare part is now ideally manufactured at the point of demand (e.g., at the location of the industrial customer). Alternatively, AM activities could take place at retailers or, for instance, at local subsidiaries, workshops, and maintenance plants in the industrial AM context. In addition, Figure 2-9 distinguishes between the decentralization of AM and its envisioned combination with extensive outsourcing to local AM service bureaus. The latter variant enables AM service bureaus to pool local or regional orders, as visible in Figure 2-9. Overall, Figure 2-9 sketches how the phases of manufacturing and distribution become blurred in both decentralized AM SCDs. In this vein, Zanetti et al. (2015, p. 139) propose that products travel through the AM SC mostly in a digital form, "tearing down the wall between production and delivery." This fits the expectation that AM business models break up established roles and vertical relationships (see Section 2.2.3).

This section has established an understanding of the chains of argument underlying the expectation of decentralized AM SCs with increasing outsourcing of manufacturing activities to AM service bureaus. On this basis, the next section provides an overview of the current state of the literature on AM SCDs and the underlying choice of manufacturing firms. It focuses on characterizing AM SCDs by their horizontal and vertical scope and discusses how these two dimensions have already been addressed in the extant OSCM literature.

### 2.3.4 Overview of the literature on the additive manufacturing supply chain design choice of manufacturing firms

This section aims to provide an overview of the knowledge on the SCD choice for industrial AM, specifically for determining the horizontal and vertical scope from the perspective of focal manufacturing firms. The earliest study dedicated to AM SCDs was published by Walter et al. (2004). After this first conceptual work about the benefits of decentralizing AM for aircraft spare parts, it took considerable time for research on AM SCDs to increase. Systematic literature reviews that are closely related to AM SCDs and provide comprehensive overviews have been conducted by Verboeket and Krikke (2019) and Kunovjanek et al. (2022). Both reviews rely on the SCOR framework to structure the (potentially disruptive) impact of AM on SCs. In addition, Ryan et al. (2017) use a systematic literature review to evaluate AM SCD scenarios and identify the "white space" for future AM SC development. Their scenarios are structured according to the order penetration point, geographic scope, and type of manufacturing. Moreover, an essential understanding for AM SCDs has been built by Holmström and his co-authors (e.g., Hedenstierna et al., 2019; Holmström et al., 2016; Holmström & Partanen, 2014; Holmström et al., 2010; Khajavi et al., 2014). This group of researchers contributes specifically to the design of AM spare parts SCs.

The studies considered in this section have been gathered by constantly monitoring the OSCM literature on AM, analog to Section 2.2.4. From this process of monitoring, two evolving streams of literature that focus on different aspects of AM SCD were identified. The two research streams partly overlap. One focuses on the concept of distributed manufacturing (DM), and AM is coined as one of its enablers. It is primarily featured in the operations management (OM) community and related journals. The concept of DM does not target the overall SCD but the geographic allocation of the manufacturing system that needs to be aligned and integrated with the overall SCD (Fine, 2000). The other stream of literature investigates the potential of AM to alter or revolutionize the traditional design of SCs. It is pronounced in the SCM community and its relevant journals. To provide an overview of the current state of the literature on AM SCDs, the following paragraphs systematize representative studies from the two identified streams of literature separately.

The concept of DM is defined as the manufacturing of products at multiple scales and locations. DM is expected to be enabled by digitalization and by new production technologies like AM (Srai et al., 2016b). The concept assumes that traditionally centralized mass production can be substituted by flexible, distributed economies that utilize local resources (Kohtala, 2015). In this sense, the related term "re-distributed manufacturing" describes the transformation from the current state of centralized mass production to the future state of geographically dispersed, small-scale production (Srai et al., 2016a). As a major advantage, DM is associated with a high delivery speed and on-demand production of customized products (Srai et al., 2016a).

Table 2-8 illustrates identified topics with an overarching character from the literature stream of DM. **Fundamentals of DM** summarizes studies that define the concept (e.g., Srai et al., 2020) and detail forms, trends, cost drivers, and industry sectors of DM. For example, Matt et al. (2014) differ between eight forms of DM, ranging from the standardization and replication of existing factories to flexible, smart, and modular model factories. They call decentral, cloud-based AM the most extreme form of DM. Moreover, additional studies embed DM within the evolution of **manufacturing paradigms**. On the development path from the paradigms of craft production to mass production, lean manufacturing, and mass customization, DM is expected to contribute to the latest paradigm of personalized production (e.g., Hu, 2013). In addition, DM is expected to drive a shift from the "global factory" paradigm to more dispersed structures, which Hannibal and Knight (2018) anticipate to be similar to "cottage industries" that existed until the 19th century. What is more, several studies closely link the concept of DM to the **Industry 4.0** terminology (e.g., Kumar et al., 2020; Olsen & Tomlin, 2020). With the support of modern information and communication technologies, AM and other Industry 4.0 technologies are expected to provide the required digital infrastructure for DM. This infrastructure is characterized by advanced automation, data sharing, real-time production control via sensors, and Internet-based collaboration. As the Industry 4.0 technologies mature, repeatable and reliable production at multiple locations becomes increasingly feasible (Srai et al., 2016b).

Table 2-8: Thematic categorization of overarching studies on DM.

| Category | Representative studies |
|---|---|
| Fundamentals of DM | **Definition:** Srai et al. (2020); Srai et al. (2016a); Srai et al. (2016b)<br>**Forms, trends, cost drivers, and industry sectors:** Matt et al. (2014); Mortara and Parisot (2016); Mourtzis and Doukas (2012); Rauch et al. (2018); Seregni et al. (2015) |
| Manufacturing paradigms | Ghobadian et al. (2020); Hannibal and Knight (2018); Hu (2013) |
| Industry 4.0 | Kumar et al. (2020); Olsen and Tomlin (2020) |

The more specific categories in Table 2-9 concretize the **technical realization** of DM. The literature focuses on cloud-based manufacturing execution systems for intelligently and effectively managing and scheduling DM. Via cloud manufacturing platforms, decentral AM resources can be centrally managed and matched with the demand for AM services (e.g., Helo et al., 2014; Mai et al., 2016). In this regard, Durão et al. (2017) propose different levels of centralized control by linking centralized control to specific activities (i.e., the design process, manufacturing process, and process of quality control). More generally, Lee et al. (2013) emphasize that DM requires effective collaboration, coordination, and risk mitigation strategies since risks are scattered compared to centralized operations. Cloud manufacturing appears to offer suitable technical solutions for DM and, as demonstrated in Section 2.2.4, is also recognized as a field for AM business model development. Moreover, extensive research deals with the **implications of DM** by comparing the costs and even more the environmental effects of DM with centralized manufacturing. DM is discussed as an enabler of circular economies[16] (e.g., Moreno et al., 2019), which is partly discussed with a direct focus on AM (e.g., Kreiger & Pearce, 2013). Interestingly, DM is recognized to entail both sustainability benefits and challenges. The latter result from the reduced resource efficiency of small-scale production, the currently insufficient level of automation, and lower equipment utilization than in centralized settings (Ford & Despeisse, 2016; Kohtala, 2015). Finally, the literature proposes various **fields of application** for DM, for example, in the high-variant/customization context (e.g., Mourtzis et al., 2012a) that is typical for AM (see Section 2.1.4). In the urban, smart-city context, small-scale DM could lead to "less vertical and horizontal complexities in comparison

[16] The concept of circular economy has emerged as a policy objective that is discussed in academics and practice. It is based on the core idea of decoupling economic growth from increasing resource consumption and promotes waste reduction (Gregson et al., 2015).

with traditional supply chains" (Kumar et al., 2016, p. 7189). In particular, micro-factories are promoted as scalable, modular, and geographically flexible production units. Also termed "on-site factories" or "container factories," their application is expected to enable lead time and inventory reductions (e.g., Rauch et al., 2015; Zanetti et al., 2015).

Table 2-9: Thematic categorization of specific studies on DM.

| Category | Sub-category | Representative studies |
|---|---|---|
| Technical realization | Cloud-based manufacturing execution systems | Helo et al. (2014); Lu et al. (2019); Mai et al. (2016); Wu et al. (2013); Yao et al. (2015) |
| | Risk management and control | Durão et al. (2017); Lee et al. (2013) |
| Implications of DM | Costs | Roca et al. (2019) |
| | Enabler of circular economies | Ashby (2016); Moreno and Charnley (2016); Moreno et al. (2019); Prendeville et al. (2016) |
| | Sustainability benefits and challenges | Despeisse and Ford (2015); Ford and Despeisse (2016); Kohtala (2015); Kreiger and Pearce (2013); Rauch et al. (2016) |
| Fields of application | High-variant/customization context | Mourtzis et al. (2012a); Mourtzis et al. (2012b) |
| | City-level hubs | Kumar et al. (2016) |
| | Micro-factories | Rauch et al. (2015); Zanetti et al. (2015) |

In comparison to the studies on DM, the stream of literature focusing on the potential of AM to alter traditional SCDs is less technically oriented and less focused on the manufacturing system and infrastructure. Furthermore, it is dominated by studies that directly deal with AM technologies and their integration into SCs. Hence, the use of Industry 4.0 terminology to aggregate AM and other currently emerging digitally dominated technologies is less pronounced than in the DM literature. Particular emphasis is put on AM spare parts SCs as common units of analysis, for example, in the aerospace industry (e.g., Khajavi et al., 2014; Liu et al., 2014) and at remote settings like military and humanitarian missions (e.g., den Boer et al., 2020; Westerweel et al., 2021) and space stations (Pérès & Noyes, 2006).

Table 2-10 structures influential SCM studies that contribute to an overarching understanding of the impact of AM. Studies summarized under the category **fundamental impact of AM on SCs** propose visions and expectations of AM SCs, for example, in terms of their length, complexity, and KPIs like costs, lead times, inventory levels, and part availability (e.g., Verboeket & Krikke, 2019). Some studies suggest specific AM SCDs, for example, by exploring the constellations of traditional actors and new actors from the AM domain (e.g., Öberg, 2022) or by drawing a development path toward increasing decentralization with growing AM maturity (e.g., Tziantopoulos et al., 2019). In addition, studies rank the impact of AM within **SCM paradigms**, analog to the embedding of DM within manufacturing paradigms. Rapid manufacturing (i.e., the use of AM for end products, see Section 2.1.1) is expected to impact the paradigms of lean and agile SCs and contribute to more flexible, demand-driven SCs (Martinelli & Christopher, 2019; Tuck et al., 2007). AM "demand" chains may emerge that combine the characteristics of both lean and agile ("leagile") SCs, as argued by Christopher and Ryals (2014). Moreover, studies take an "inside view" on SCs by exploring how firms adopt AM, collaborate, and leverage the potential of AM technologies in the wider SC (Luomaranta & Martinsuo, 2020). For example, Oettmeier and Hofmann (2017) consider inter-organizational (i.e., supply- and demand-side) benefits when exploring manufacturing firms' **AM adoption decisions**. A similar "inside view" is taken in studies that identify and assess which **applications** would benefit from AM by accounting for the SC effects of the switchover from traditional manufacturing technologies to AM. These studies are closely tied to spare parts/after-sales SCs (Knofius et al., 2016). For example, Heinen and Hoberg (2019) show how switching a small share of slow-moving spare parts to AM can already become economically beneficial when comparing the higher production costs of AM with the potential for cost reductions based on lower inventory levels, fewer orders, and less transportation. In a similar vein, Knofius et al. (2019) assess the use of AM for redesigning and consolidating parts for AM (see function integration in Section 2.1.3) with a total cost perspective.

Table 2-10: Thematic categorization of overarching studies on AM SCD.

| Category | Representative studies |
|---|---|
| Fundamental impact of AM on SCs | **(Disruptive) impact of AM on SCs:** Ben-Ner and Siemsen (2017); Chan et al. (2018); Durach et al. (2017b); Mohr and Khan (2015); Waller and Fawcett (2014)<br>**SCD:** Holmström et al. (2016); Kunovjanek et al. (2022); Öberg (2022); Ryan et al. (2017); Tziantopoulos et al. (2019); Verboeket and Krikke (2019); Zijm et al. (2019) |
| SCM paradigms | Christopher and Ryals (2014); Chung et al. (2018); Martinelli and Christopher (2019); Tuck et al. (2007) |
| AM adoption in SCs | Luomaranta and Martinsuo (2020); Oettmeier and Hofmann (2017); Rylands et al. (2016); Thomas (2016) |
| Identification of AM applications | **Applicability of AM/part selection:** Heinen and Hoberg (2019); Knofius et al. (2016); Westerweel et al. (2018)<br>**Part consolidation:** Knofius et al. (2019) |

The studies in Table 2-11 provide a more specific understanding for AM SCD decisions, their decision implications, and decision context. In doing so, Table 2-11 starts by sorting studies according to common **AM SCD decisions** in the phases of procurement, manufacturing, warehousing, and distribution, as introduced in Section 2.3.1 (see Chandra & Grabis, 2007; Kouvelis et al., 2006). Studies investigate how AM affects the procurement function of manufacturing firms (Meyer et al., 2021) and public procurement in light of the COVID-19 pandemic (Meyer et al., 2022). Moreover, they provide cost comparisons for make versus buy scenarios (e.g., Baldinger et al., 2016; Ruffo et al., 2007) and specific insights into the benefits of dual sourcing AM and traditionally manufactured parts (Knofius et al., 2021). For the production capacity and strategy, studies develop realistic cost models for AM (Baumers & Holweg, 2019) and mainly focus on the discussion of decentralized versus centralized AM, especially for spare parts SCs (e.g., Khajavi et al., 2018; Khajavi et al., 2014; Liu et al., 2014). As further outlined in Table 2-11, the current discussion on warehousing strategies focuses on the alternatives of stock (i.e., make-to-stock) versus print (i.e., make-to-order), for example, for spare parts (Song & Zhang, 2020) and consumer products at retailers (e.g., Arbabian & Wagner, 2020). Moreover, studies investigate the impact of AM on the distribution strategy and selected transportation modes, which overlaps with the literature background provided in Section 2.2.4 for the positioning of LSPs in AM.

Studies dealing with the **decision implications** of the AM SCD choice explore the resilience of AM SCs and the sustainability and social implications. In fact, Hohn and Durach (2021) raise awareness that manufacturing reshoring can, in the short term, create negative social effects. For example, they find that reshoring is likely to temporarily increase the competitive pressure and worsen working conditions in the apparel SC. Finally, Table 2-11 summarizes studies that characterize the **decision context** of the AM SCD decision. These studies focus on how AM SCDs are integrated with traditional manufacturing technologies. They discuss stand-alone AM versus the interaction of AM and traditional manufacturing technologies in SCs with a combinational or co-location-based approach. Such an approach is characterized by AM machines working alongside traditional tool-based machines (e.g., Braziotis et al., 2019).

Table 2-11: Thematic categorization of specific studies on AM SCD.

| Category | Sub-category | Representative studies |
|---|---|---|
| AM SCD decisions | Procurement/ sourcing | **Procurement function:** Meyer et al. (2021, 2022); Muhammad et al. (2022); Pahwa et al. (2018) |
| | | **Make-or-buy decision:** Baldinger et al. (2016); Chaudhuri et al. (2021); Ruffo et al. (2007) |
| | | **Ease of outsourcing:** Berman (2012); Hedenstierna et al. (2019); Manda et al. (2018) |
| | | **Secure outsourcing:** Kurpjuweit et al. (2021); Yampolskiy et al. (2014) |
| | | **Dual sourcing:** Knofius et al. (2021) |
| | Manufacturing capacity/costs | **Production planning:** Jonsson and Holmstrom (2016) |
| | | **Production costs:** Baumers et al. (2017); Baumers and Holweg (2019); Ruffo et al. (2006) |
| | Manufacturing location | **Central versus decentral:** Chekurov et al. (2018); Emelogu et al. (2019); Holmström et al. (2010); Khajavi et al. (2018); Khajavi et al. (2014); Li et al. (2017b); Liu et al. (2014); Walter et al. (2004) |
| | | **Remote locations:** De la Torre et al. (2016); den Boer et al. (2020); Pérès and Noyes (2006); Westerweel et al. (2021) |
| | Warehousing | **Stock versus print:** Arbabian (2022); Arbabian and Wagner (2020); Chen et al. (2021); Song and Zhang (2020) |
| | Distribution | Barz et al. (2016a, 2016b); Boon and van Wee (2018); Chen (2017) |
| Decision implications | Resilience | Belhadi et al. (2022) |
| | Sustainability and social responsibility | Despeisse et al. (2017a); Hettiarachchi et al. (2022); Hohn and Durach (2021); Holmström et al. (2017) |
| Decision context | Interaction of AM and traditional manufacturing | Braziotis et al. (2019); Khajavi et al. (2015); Sasson and Johnson (2016); Strong et al. (2018) |

When focusing on the insights provided by the representative studies from both streams of literature into the horizontal and vertical scope to characterize AM SCDs, it is striking that the horizontal scope is more prevalent than the vertical scope. Decentralization is inherently tied to the concept of DM, entailing that the discussion of centralized manufacturing versus DM emerges as a natural consequence. Moreover, multiple SCM studies compare centralized versus decentralized AM SCDs. In contrast, insights into the vertical scope and how the AM governance structure is defined by AM make-or-buy decisions can be found in a limited set of studies from the two streams of literature.

**Horizontal scope:** Many arguments in the extant literature raise expectations for the decentralization of AM SCs. However, low-cost, standard, and simple components are ideal for mass production at a **central** location (Kumar et al., 2020). Such parts are expected to be traditionally manufactured, even though they may be technically eligible for AM (Chekurov et al., 2018). Consequently, standard components like screws, nuts, and bolts without much fluctuation in demand are predicted to be excluded from the advantages of decentralization and of AM in general (Ben-Ner & Siemsen, 2017; Holmström et al., 2010). Centralized AM may be more cost-efficient, even with enhanced AM machine performance and reduced AM machine costs (Roca et al., 2019). However, previous work, including the early study of Walter et al. (2004), argues that centralized operations cannot tap the full potential of AM. The literature expects products from the typical application fields of AM, the high-complexity, high-variant, or low-volume contexts (see Section 2.1.4), to be ideal for **decentralized** operations (e.g., Kumar et al., 2020). In particular, concrete expectations exist for decentralized spare parts SCs (e.g., Ben-Ner & Siemsen, 2017; Chekurov et al., 2018; Holmström et al., 2010; Liu et al., 2014; Tuck et al., 2007). The economic deployment of AM at decentralized locations, however, depends on the utilization of the decentral equipment and, thus, the availability of sufficient decentral demand (Liu et al., 2014). Ideally, parts can be manufactured with the same AM equipment and require limited post-processing steps (Roca et al., 2019). Furthermore, **extremely decentralized** AM is seen as beneficial in geographically isolated systems[17], where the access to traditional spare parts is intermittent and limited to fixed replenishment intervals. Mobile AM machines and micro-factories are investigated in empirical settings such as space stations (Pérès & Noyes, 2006), military missions (Westerweel et al., 2021), humanitarian missions (De la Torre et al., 2016), and construction sites (Rauch et al., 2015). These settings have in common that they are characterized by huge geographic distances, harsh conditions, a lack of local dealers/workshops, and uncertain suppliers (De la Torre et al., 2016; Rauch et al., 2015). Additional application fields are expected to emerge in industries that share these characteristics, for example, in the mining, oil and gas, and shipping industry (Westerweel et al., 2021). The concept of **mobile** AM *en route* in trucks should also be mentioned since studies refer to it in the context of Amazon's patent[18] (e.g., Zanetti et al., 2015). However, manufacturing *en route* puts high requirements on the robustness of the AM process, and, so far, viable use cases are lacking in the literature. In addition, it should be noted that using mobile AM machines in trucks or at remote/isolated locations poses additional technological challenges, for example, in terms of machine calibration, energy supply, availability of certified raw materials, secure digital infrastructure, qualified workforce, and atmospheric conditions (De la Torre et al., 2016; den Boer et al., 2020; Walter et al., 2004; Westerweel et al., 2021). Finally, deviating from extreme decentralization, the literature also raises expectations for "moderate" decentralization and hybrid forms. The literature suggests that **AM hubs**, with their limited geographic scope, can improve equipment utilization and, hence, the economic efficiency of manufacturing activities since orders can be pooled (Braziotis et al., 2019). According to Khajavi et al. (2018, p. 1178), a hub SCD "combines the benefits of centralized production with the flexibility of local manufacturing without the huge costs related to it." City-level hubs may be a more realistic alternative than home 3D printing for consumer goods (Boon & van Wee, 2018; Kumar et al., 2016). On the industrial side, strategic infrastructure nodes like ports and airports are evaluated as suitable locations for AM hubs since firms can leverage the intact transportation infrastructure and energy supply (den Boer et al., 2020). Moreover, decentralized AM can be combined with different degrees of **central control**. In today's connected industrial environment, with the availability of technical solutions like cloud-based manufacturing execution systems (e.g., Helo et al., 2014; Mai et al., 2016), AM fosters the spatial independence of tasks in the SC and suggests adjusted concepts for work organization. Knowledge-intensive, highly specialized tasks (e.g., the design process) can remain at a centralized location while more repetitive and standardized tasks can be decentralized. As a result, the location of highly trained engineers and design specialists is centralized, and – when taking it to the extreme – only the physical AM production process is performed decentrally (Durão et al., 2017).

**Vertical scope:** The demand for AM parts should be considerably high, and firms should be willing to develop expertise in AM when selecting **in-house** AM (Chaudhuri et al., 2021). Vice versa, **outsourcing to AM service bureaus** is expected to enable firms to concentrate on their core competencies outside AM (Manda et al., 2018). For example, it may be feasible for retailers to integrate polymer 3D printing into their service portfolios (Arbabian, 2022; Arbabian & Wagner, 2020; Chen et al., 2021). However, in other settings like the healthcare SC, hospitals may not be able to manage in-house AM in addition to their day-to-day procedures (Chaudhuri et al., 2021). Similarly, den Boer et al. (2020, p. 8) highlight that outsourcing AM in the military SC avoids high AM

[17] Pérès and Noyes (2006, p. 490) define an isolated system as a system "in which the part supplying is made difficult because of the specific environment which is not really adapted and for which the storage of spare parts implies space constraints incompatible with the size of such systems." They differ for such a system between temporal isolation (e.g., obsolete parts) and geographic isolation.

[18] The patent of Amazon for on-demand 3D printing services for consumers was granted in 2018. The patent proposes that STL-files can be sold via the Amazon platform and printed by a 3D printer installed in a truck on its way to the customer. The advantages of this idea lie in the minimization of lead times and inventory costs (Amazon Technologies, 2018).

machine costs and enables the military to "benefit from AM, while still focusing on its core-business." When it comes to leveraging outsourcing as a means of establishing decentralized AM, some studies emphasize the ease and flexibility of outsourcing the manufacturing process to AM service bureaus (e.g., Berman, 2012; Hedenstierna et al., 2019). The arguments rest on the seamless transfer of digital product specifications and on the general-purpose AM machines leading to a commoditized production infrastructure (Sasson & Johnson, 2016). Such a commoditized manufacturing infrastructure is expected to enable the pooling of orders in decentralized settings (Holmström et al., 2010). AM service bureaus are predicted to offer their services for multiple customers and applications. Manufacturing firms, on the other hand, may find it a challenge to establish and manage a decentral supplier base. In this sense, Zanetti et al. (2015) suggest **intermediate web-based platforms** for coordinating and aggregating orders for outsourcing to AM service bureaus. They provide an example of a collaborative platform in the context of consumer 3D printing. Similarly, Pahwa et al. (2018) propose a reverse auction mechanism to match consumers' bids with 3D print shops via a platform. Moreover, for industrial AM, Chekurov et al. (2018, p. 92) propose the cooperative outsourcing of multiple manufacturing firms by establishing a jointly owned "international service bureau network." This centrally operating service center acts as a single entity that coordinates the manufacturing of AM spare parts by subcontracting further partners close to the maintenance plants where the parts are demanded. To overcome IP concerns in AM outsourcing, blockchain technology has been proposed for simplifying secured outsourcing to decentral AM service bureaus (Kurpjuweit et al., 2021). Moreover, Yampolskiy et al. (2014) suggest a secure outsourcing model by splitting the activities of developing manufacturing parameters and performing the actual manufacturing process between two independent service providers. In addition, the trends of increased **sharing and leasing** of manufacturing infrastructure is present in the literature and could lead to hybrid, more collaborative governance structures. Khajavi et al. (2014) raise the idea that manufacturers can share their networks for supplying AM spare parts to their point of demand. It is indeed the commoditized manufacturing infrastructure that can enable the increased sharing and leasing of manufacturing capacities. For example, Sasson and Johnson (2016) suggest that manufacturing capacities could turn into regional, multi-product "supercenters" where low volumes of different products with no asset specificity and zero changeover costs are manufactured. Heterogeneous orders could be exchanged between such regional AM "supercenters" for the case that demand exceeds their capacity (Sasson & Johnson, 2016). Overall, manufacturing firms are expected to establish more agile and flexible procurement functions that are capable of handling the flexible outsourcing and trading of excess capacities (Hedenstierna et al., 2019; Meyer et al., 2021).

In summary, the extant OSCM literature provides multiple arguments that point toward decentralized AM SCs in both identified streams of literature. Use cases are described in spare parts SCs and in remote settings. In addition, "moderate" variants of decentralized AM, for example, regional hubs and facets of centralized control combined with decentralized AM activities, are proposed. Concerning the AM governance structure, previous work highlights the ease of outsourcing AM and the opportunities for sharing commoditized manufacturing capacities. Moreover, the literature suggests technical solutions for real-time monitoring of decentralized AM (e.g., cloud-based AM), secure outsourcing (e.g., blockchain-based data transfer), and the efficient selection of local outsourcing partners (e.g., via an "international service bureau network" as a third party or intermediate web-based platform). Figure 2-10 structures and illustrates the identified variants of increasing decentralization and outsourcing as to how products, ultimately, approach the point of demand.

Some of the variants from Figure 2-10 give the **impression of being visionary**, in particular, when considering the technical challenges emerging industrial AM technologies currently face (see Section 2.1.3). Other studies arrive at similar conclusions when reviewing the state of the literature. For example, Knofius et al. (2019, p. 270) summarize, "we mostly find conceptual and visionary considerations for the use of AM technologies in supply chains." At the same time, examples from practice demonstrate that manufacturing firms are currently implementing AM in their SCs and selecting specific SCDs, for example, in-house AM at a central location (GE Additive, 2018). In light of the current high expectations and visions for AM SCDs, it is not sufficiently understood how these focal manufacturing firms react to AM; to be precise, how far they rely on external capacities and are in the process of decentralizing AM. In this vein, in-depth investigations are needed for the vertical scope of AM SCs, including research on AM sourcing concepts and elaborations on the value of in-house and outsourced AM, as also proposed by Kunovjanek et al. (2022). Similarly, for the horizontal scope, visions of decentral, mobile, or platform-based AM and thresholds that need to be overcome can be extracted from the literature, as has, for example, been illustrated in a roadmap by Verboeket and Krikke (2019). However, there is limited knowledge on what actually drives manufacturing firms in their selection of these specific SCDs; hence, what rationales currently influence manufacturing firms' inner decision mechanisms and their choice for a specific degree of geographic dispersion. Building such an understanding is a prerequisite for making sound predictions for prevailing AM SCDs.

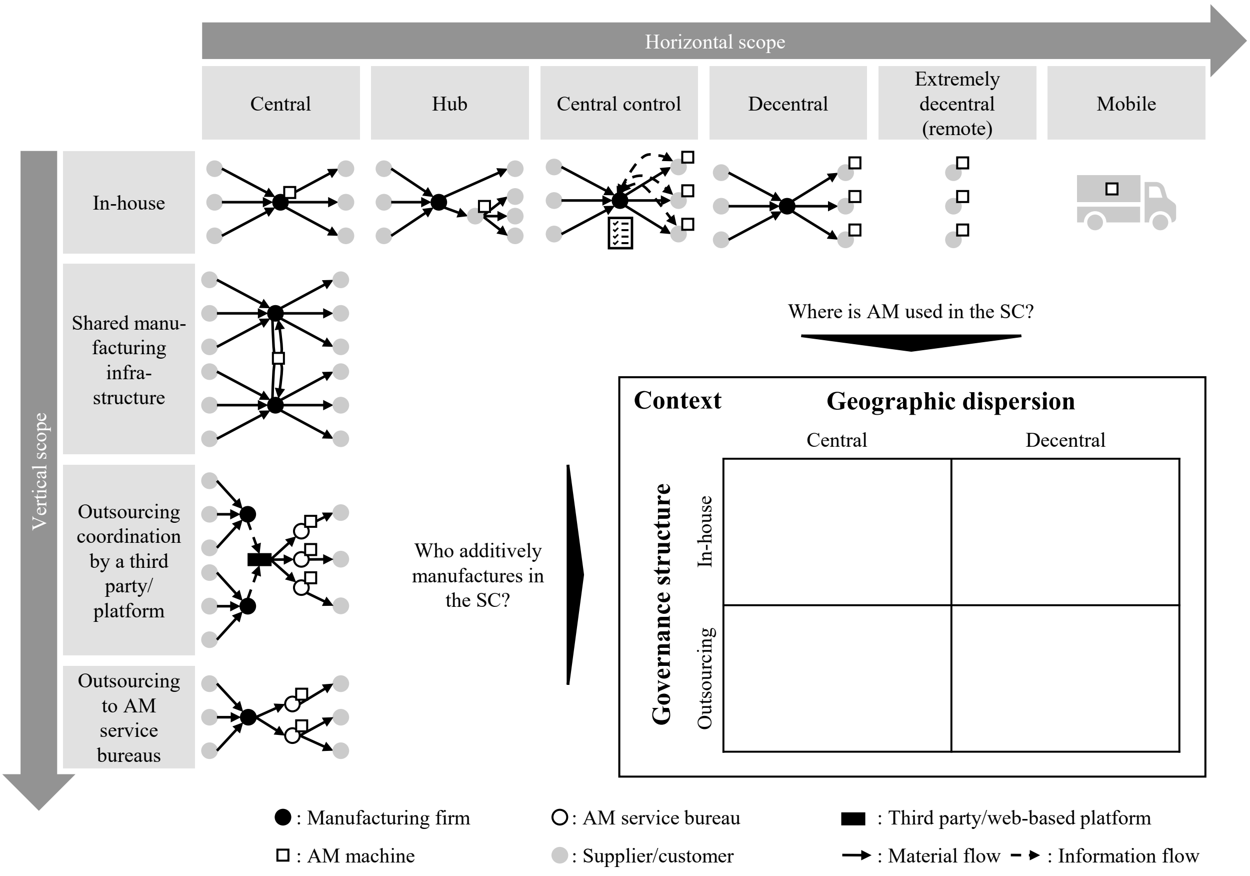



Figure 2-10: Visions of AM SCDs selected by manufacturing firms.

Finally, the current state of the literature reveals that only limited research has been conducted on how **AM is integrated into a specific SC context**. The studies of Braziotis et al. (2019), Khajavi et al. (2015), Sasson and Johnson (2016), and Strong et al. (2018) provide initial insights into how AM can be used as stand-alone technologies or co-located with traditional manufacturing technologies. For example, manufacturing firms may find their individual equilibrium in a "middle-of-the-road scenario" (Sasson & Johnson, 2016, p. 83), where AM is used for specific applications (e.g., complex, low-volume, sporadic demand) but does not substitute traditional mass production. Moreover, switching from AM to traditional manufacturing emerges as a suitable combination to stay flexible and counter financial risks in new product launches (Khajavi et al., 2015). Hence, it is important to consider such interactions between AM and traditional manufacturing technologies. Chan et al. (2018) even claim that one of the reasons why AM currently does not fulfill its promises is that the technologies are not well integrated into SCs. When taking this thought one step further, not only the interweaving of AM with traditional manufacturing technologies but also its embedding in an industry context should be considered, as reflected in the calls for building more context- and industry-specific domain knowledge for AM (Ford & Despeisse, 2016; Hohn & Durach, 2021; Rehnberg & Ponte, 2018). For example, Section 2.1.2 has created awareness for the economic and technological implications of industrial AM technologies. These characteristics will likely have an influence on emerging AM SCDs (e.g., in terms of financial requirements and necessary pre- and post-processing steps of specific AM technologies) and lead to different AM SCDs compared to less regulated (e.g., consumer-oriented) contexts.

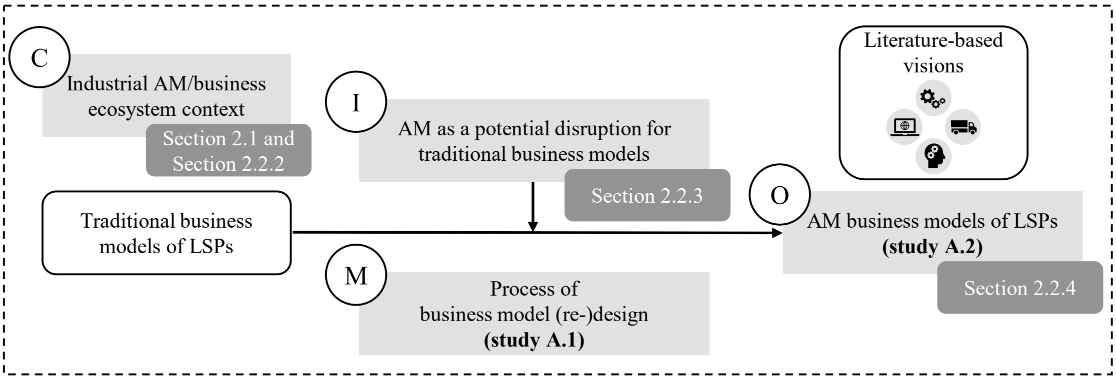
Based on the identified tendencies in the OSCM literature and the **research gap** discussed, Figure 2-10 provides a scheme that serves as a starting point for how this thesis (part B) addresses the research gap with the overarching research question RQB. Currently emerging SCDs are explored from the perspective of focal manufacturing firms within the specific context of industrial AM and in the illustrated polar matrix of geographic dispersion and governance structure. Next, the conceptual foundations from Sections 2.1 to 2.3 are summarized in a conceptual framework.

## 2.4 Derived conceptual framework

Chapter 2 has built literature-based knowledge to concretize and define the conceptual scope of this thesis and its embedding in the background literature. Moreover, it has detailed the research gaps that are addressed in parts A and B. In this sense, **Section 2.1** has provided an up-to-date understanding of the industrial AM context and distinct characteristics of the technologies in comparison to traditional manufacturing technologies. The history of AM technologies and their typical four-step manufacturing process chain were described to enable an elementary assessment of the technological and economic implications of AM. Additionally, the advantages and challenges that come with current AM technologies and their resulting fields of application in low-volume, high-variant, and high-complexity contexts are necessary building blocks for understanding why AM is likely to drive the (re-)design of business models and SCs. In summary, Section 2.1 has drawn a picture of AM comprising inherently digital and flexible manufacturing technologies for which economies of scale are of minor relevance. The traditional, highly specific, and interdependent manufacturing infrastructure becomes general-purpose equipment that is compact, transportable, and involves low skill requirements for the ideally one-step AM process. However, Section 2.1 has also raised awareness for the comparably high costs of AM, problems with quality, accuracy, and reliability, as well as technical constraints and limited education and acceptance within firms.

Based on the outlined specifics of the industrial AM context, **Section 2.2** has aimed to deepen the motivation and provide a comprehensive overview of the literature basis for the overarching research question RQA. Figure 2-11 uses the CIMO-logic (Denyer et al., 2008) to summarize the insights provided and, with that, it serves as a conceptual framework for tackling RQA in this thesis. As outlined in Figure 2-11, the introduced AM business ecosystem is proposed as the concrete *context* in which incumbents like LSPs position themselves in AM and where AM business models emerge. Interestingly, the business ecosystem challenges incumbents not only as predestined users of AM technologies but also as active providers of AM-specific products and services. Moreover, awareness for the possible difficulties that incumbents currently face in their development of AM-specific business models has been created, see Figure 2-11. The *intervention* of AM, hence, its power to trigger a process of business model (re-)design, directly results from the digital and flexible nature of AM technologies. Most noteworthy is the expected quest for more open and decentralized business models that encompass offers of blurring product-service systems. With incumbents and new actors from the AM domain placing AM machines close to (e.g., in retail stores) or at the point of demand (e.g., at maintenance plants), the role of LSPs warrants attention. What makes the role of LSPs special lies in the direct dependence of their traditional business models on their customers' (e.g., manufacturing firms and retailers) development of AM business models. Their customer dependence and required adaptability to their customers' demand in order to survive in the highly competitive logistics market are expected to urge them to become active in AM by initiating a *mechanism* of business model (re-)design. Finally, the overview of the state of the AM business model literature has revealed that there is currently no focus on this mechanism, namely the successive and likely cyclic process of trial-and-error AM business model development starting from LSPs' traditional business models. Instead, the literature currently provides mostly conceptually derived visions of "finished" AM business models for LSPs (see Figure 2-11). Thus, the literature contributes to the expected *outcome* without building an in-depth understanding of the mechanisms, for example, through the collection of empirical insights from LSPs. Study A.1 directly targets the mechanism and underlying causal processes that LSPs undergo to provide a realistic picture of how and why LSPs currently respond to AM. In addition, study A.2 focuses on the outcome to explore which generic AM business models could emerge, substantiated with perspectives collected from LSPs and their partners/competitors and customers in industrial AM SCs.

RQA: *How* and *why* does industrial AM impact the business model development of LSPs?

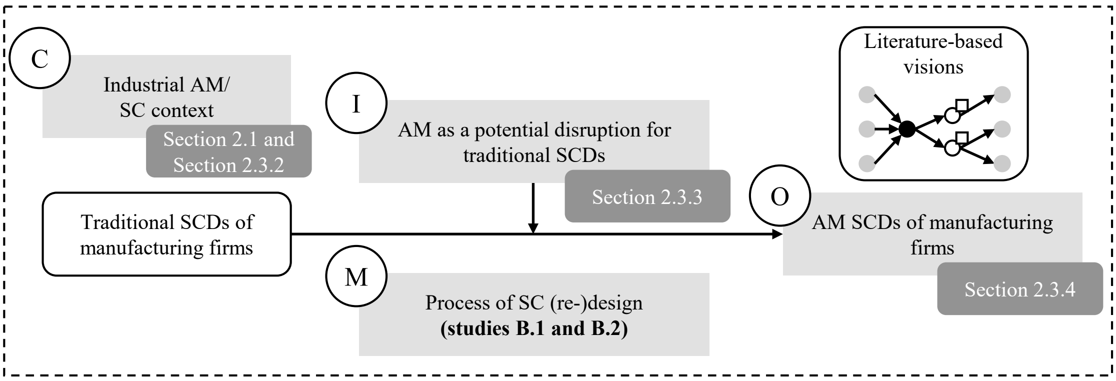



| CIMO-logic | Provided conceptual foundations for the AM business model development of LSPs |
|---|---|
| **Context** | ▪ Overview of the **AM business ecosystem** and of the twofold role of incumbents (as users of AM and as providers of AM-specific products and services)<br>▪ Building of an understanding of how the **emerging stage** of AM and the **nascent market** setting complicate incumbents' development of AM-specific business models:<br>– Little consensus about required capabilities for AM<br>– Potential conflicts of AM with existing business models (firms' resource base)<br>– Existing organizational structures may not be suitable for the integration of AM<br>– Overlapping services and products of actors and no clear structure in the AM business ecosystem |
| **Intervention** | ▪ Incumbents are expected to be under pressure to adapt their business models to AM<br>▪ The characteristics of AM change the **way incumbents can create, capture, and appropriate value** to their customers compared to traditional manufacturing:<br>– AM fosters more open, decentralized business models that encompass product-service systems<br>– AM can offer additional customer value (e.g., for niche products, increased service level)<br>– AM requires different revenue models and risk management strategies for the digitally held IP<br>▪ **LSPs** are in a special position since their traditional business directly depends on the reactions of their customers (e.g., manufacturing firms) to AM |
| **Mechanism** | ? |
| **Outcome** | ▪ Creation of awareness that the understanding of the effects of AM on the core services of LSPs (e.g., transportation and warehousing) is so far insufficient in the literature; despite limited quantification, the expectation of an **overall decline** in the **demand for logistics services** prevails<br>▪ Summary of **literature-based visions** of AM business models for LSPs, including LSPs in the role of manufacturers, as developers of digital infrastructure, as providers of traditional logistics services, and as consultants/service managers |

Figure 2-11: Conceptual framework for the overarching research question RQA.

Analog to Section 2.2, **Section 2.3** has served to illuminate the specific motivation behind the overarching research question RQB and built knowledge based on the extant OSCM literature. Again, Figure 2-12 applies the CIMO-logic to derive a conceptual framework for guiding the work on RQB in this thesis. AM SCs are expected to emerge within the *context* of traditional SCs. Such traditional SCs have been introduced with a typical design that is known for its length and complexity (horizontal scope) and the involvement of multiple, highly specialized firms (vertical scope). Indeed, the horizontal and vertical scope have emerged as suitable dimensions to characterize and differentiate SCDs in this thesis. Moreover, the dominant position of focal manufacturing firms that determine the SCD to a large extent has been established, as summarized in Figure 2-12. The *intervention* of AM, that is, the expectation of AM to initiate a process of (re-)design of manufacturing firms' traditional SCs, is based, again, on the inherently digital and flexible nature of AM. For the horizontal scope, the prediction of AM to shrink the SC and enable local, decentralized manufacturing to contribute to the trend of reshoring has been described. For the vertical scope, the expectation of AM to ease outsourcing to generalized AM service bureaus that can pool the orders of many customers complements the picture. Visions of decentralized, outsourced SCs as the expected *outcome* dominate the two identified research streams, the OM-centric literature on DM and the SCM literature focused on the AM SCD choice. Intermediate and "moderate" forms of decentralized AM as well as technical solutions and coordination mechanisms for outsourcing have been extracted from the literature. However, insights into the *mechanism* of how and why focal manufacturing firms are currently selecting specific SCDs for AM are scarce. Both studies of part B contribute to building an understanding of the mechanism, with a focus on the governance choice (study B.1) and the interplay of both dimensions for the SCD choice (study B.2).

RQB: *How* and *why* does industrial AM impact the SCD choice of manufacturing firms?




| CIMO-logic | Provided conceptual foundations for the AM SCD choice of manufacturing firms |
|---|---|
| **Context** | ▪ Introduction to the traditional SCD that has been particularly dominant in labor-intensive industries:<br>– **Horizontal scope:** long, "fine-sliced," and complex global SCs with centralized mass production to achieve economies of scale, high standardization, and high division of labor<br>– **Vertical scope:** multiple, highly specialized firms with a low degree of vertical integration<br>▪ Raised awareness for the current trend of reshoring and increasing criticism of traditional SCDs (e.g., for their exposure to risks of disruption and their environmental footprint)<br>▪ Focal manufacturing firms as the "dominant producers" determine the SCD to a large extent |
| **Intervention** | ▪ Expectation of AM to foster reshoring and lead to shorter SCs with local production:<br>– **Horizontal scope:** shift from centralized mass production to decentralized small-scale production; simplified, shorter, more flexible, and responsive SCDs<br>– **Vertical scope:** flexible outsourcing of AM to pools of local AM service bureaus; based on commoditized production infrastructure, low skill requirements, and ease of sharing the digitally encapsulated product specifications |
| **Mechanism** | ? |
| **Outcome** | ▪ Identification of **two streams** of literature on DM (from the OM community) and AM SCD (from the SCM community); prevailing expectation of **decentralized SCs** with **extensive outsourcing** in both streams<br>▪ Decentralized (in contrast to centralized) and outsourced (in contrast to in-house) AM SCs are extreme SCDs; the literature suggests **intermediary forms and variants** that may be applicable in specific contexts |

Figure 2-12: Conceptual framework for the overarching research question RQB.

# 3 Theoretical and methodological foundations

Chapter 3 complements the conceptual foundations derived in Chapter 2 by aiming to justify and characterize the selected theoretical and methodological foundation for this thesis. For this purpose, this chapter starts by compiling relevant theoretical and methodological principles, which are then transferred to the four studies to enable their classification. While Section 3.1 focuses on the understanding of theory within this thesis, Section 3.2 provides insights into the applied methodologies. Overall, the two sections foster the understanding of the research design of each study and are the basis for deriving a theoretical-methodological framework in Section 3.3.

## 3.1 Understanding of theory

This thesis is based on a broad understanding of the different facets of theory. It applies multiple theoretical lenses and contributes with the presented results to theory development on different levels, as will be explained in this section. Therefore, Section 3.1.1 starts with positioning this thesis within addressed research disciplines. Next, the selected theoretical lenses are classified and described in Section 3.1.2. The section closes with common distinctions of the relationship between theory and research that are then discussed for the four concrete studies in Section 3.1.3.

### 3.1.1 Positioning of this thesis within research disciplines

This thesis is positioned at the **interface of business model research and OSCM research**. The term OSCM research combines the two interwoven research communities of OM and SCM research. The novel AM process has diverse consequences from an OM perspective, for example, in terms of its flexibility, quality, speed, and costs (Olsen & Tomlin, 2020), as described in Section 2.1. These operational consequences of AM are reflected in all four studies. Furthermore, the research presented for LSPs' business model dynamics (study A.1) and generic AM business model configurations (study A.2) is closely related to business model research and the management of the logistics function within the broad research field of SCM. The foundations of SCM are also relevant for the selected firm-centric perspective for investigating AM make-or-buy decisions (study B.1) and even more so for the network perspective applied to explore the AM SCD choice (study B.2). In addition, fundamental chains of argument from the strategic management community infuse the studies. The following classifies the research disciplines which this thesis addresses, as outlined in Figure 3-1.

Figure 3-1 illustrates the research hierarchy of logistics management (LM), OM, and SCM. In addition, it embeds the introduced research disciplines and especially the business model concept within the terminology of **strategic management** research. Indeed, the strategic management community has struggled to agree on a clear role for business models in theory and practice (DaSilva & Trkman, 2014), which complicates the positioning of the business model concept. However, several suggestions exist for establishing a relationship between the business model concept and a firm's strategy, and this thesis follows the chains of argument of Porter (1996): The fundamental question of strategic management is how firms can achieve a sustained competitive advantage (Teece et al., 1997). This question points to the need to achieve differentiation through a value-creating strategy that cannot be duplicated by competitors (Barney, 1991). Such differentiation can be accomplished by delivering greater value to customers, comparable value at lower costs, or by both. Firms perform multiple activities to create and deliver their products and services to their customers, and all these activities can generate cost and/or value advantages (Porter, 1996). In this sense, Porter (1996, p. 68) defines strategy as the "creation of a unique and valuable position, involving a different set of activities." This definition implies that the strategy of a firm determines a higher-order choice of activities and acts as an overall plan of action. The business model of a firm results from the choice of activities and, hence, reflects the realized strategy by defining the "logic" through which a firm competes[19] (Casadesus-Masanell & Zhu, 2013). Moreover, it is established that the selected activity system and, thus, the business model goes beyond the boundaries of a firm. Following the activity system perspective of Zott and Amit (2010), the business model defines the structure of a firm's value chain. In this context, the value chain encompasses the various and discrete processes that a firm is involved in (Demil & Lecocq, 2010). This disaggregation of the activities of a firm facilitates gaining an understanding of the costs of the activities and of their potential for differentiation. In addition, it establishes that a firm's value chain is linked with the activities of other actors, like suppliers, partners, and customers. Based on such a boundary-spanning nature, a firm's business model is focused toward the total value creation of all actors involved in its activities. Consequently, changing or innovating a business model (e.g., in light of AM) entails a reconfiguration of a firm's value chain to meet its competitive strategy for AM. Thereby, a firm may get involved in novel activities, establish new links, and interact with different actors (Rask & Günzel-Jensen, 2019).

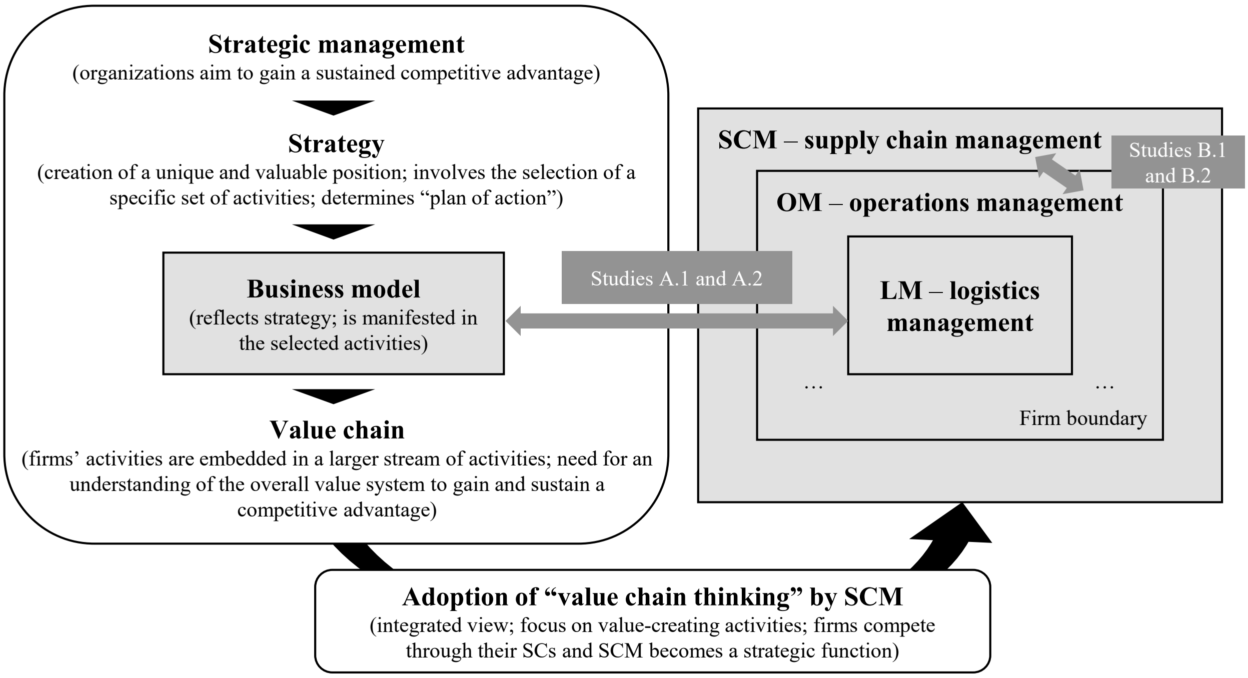



Figure 3-1: Positioning of this thesis at the interface of OSCM and business model research (the right part of the figure is based on the hierarchy of research focus according to Mentzer et al. (2008)).

The outlined concepts of strategic management have been taken up by **modern SCM** (see Figure 3-1). Traditionally, SCM used to be a function that supports organizations in the implementation of their strategy (Ketchen & Hult, 2007). However, based on Porter's (1985) understanding that firms' value-creating activities cannot be isolated but require an integrated view of the value chain, the theoretical perspective on SCM has changed. Today, organizations do not compete solely on a "firm by firm" basis but rather on the level of "supply chain versus supply chain" (Ketchen & Hult, 2007). With that, the traditional SC turns into a "value" SC and SCM into a strategic function (Christopher & Holweg, 2011; Ketchen & Giunipero, 2004). In this vein, Stank et al. (2005, p. 27) formulate, "the objective of SCM is creation of strategic differential advantage obtained by the total value delivered to end-customers." Superior SCs that enable strategic differentiation have specific characteristics, including the ability to react quickly to changes (agility), to respond to

[19] Note that this distinction between strategy and business model is not straightforward, often misunderstood, and discussed from different viewpoints in the literature (Osterwalder et al., 2005; Rainbird, 2004). For example, Dahan et al. (2010) propose that the business model of a firm describes a state while the strategy can be understood as the plan of how to move to a desired future state. Magretta (2002) emphasizes that a business model describes how the pieces of a firm fit together, but – in contrast to strategy – does not consider any competition.

changes (adaptability), and to ensure consistent interests among the actors (alignment) (Ketchen & Hult, 2007). For the case of AM, study B.1 and even more study B.2 adopt the value chain thinking by looking at SCs as structures that allow firms to achieve their competitive strategies for AM.

The value chain thinking is translated from **SCM** to **OM** (Rainbird, 2004) and **LM** (Christopher, 2011). Generally speaking, the three interrelated research disciplines are oftentimes referred to jointly. For a differentiated view within this thesis, Figure 3-1 relies on Mentzer's et al. (2008) proposed hierarchy of the three research disciplines. The characteristics of SCM to cross organizational boundaries, achieve linkages and coordination between the entities of a SC, and its emphasis on relationship management set it apart. OM is focused on the firm, which contrasts with the overarching nature of SCM (Mentzer et al., 2008). At its core, OM is concerned with the management of how resources (inputs) are transformed in a controlled and value-adding process into products and services (outputs) that meet a required quality level (Kumar & Suresh, 2009). OM is oftentimes assessed as a broad concept that is visible throughout all departments of a firm (e.g., Krajewski & Malhotra, 2022; Mentzer et al., 2008). Alternatively, OM is partly also seen as one of the three major functions within a firm, next to the marketing and finance function (e.g., Greasley, 2020). In comparison, LM is commonly assessed as a narrower concept within the functional management of firms. The logistics function essentially focuses on the flow of products and information within or between the entities in a SC (Burgess et al., 2006; Christopher, 2011). LM has a strong planning orientation, which differs from the relationship orientation of SCM (Christopher, 2011). It is concerned with the effective movement and storage of products to achieve a place and time transformation (Chase et al., 2006). Consequently, logistics research deals with the systematic management of logistics functions, for example, of facilities, transportation, inventory, materials, and information (Mentzer et al., 2008; Novack et al., 1992). Firms manage their logistics function in-house or – as relevant for the studies A.1 and A.2 of this thesis – with LSPs as third-party providers for logistics services.

In summary, the outlined research disciplines of OSCM and business model research serve to define the relevant literature background and discuss the findings of the four studies. Furthermore, they provide the understanding of business models as a reflection of a firm's competitive strategies and of SCs as structures that can contribute to firms achieving their competitive strategies. This understanding is reflected and strengthened in the four studies. Following this classification of the four studies within existing research disciplines, the following section deals with the concrete use of theory.

### 3.1.2 Selected theoretical lenses

Generally speaking, research tends to be either practice- and policy-oriented or theory-oriented (Dul & Hak, 2008). Theory-oriented research aims at contributing to theory development in a specific field, whereas practice- or policy-oriented research aims at building knowledge for specific practitioners (Dul & Hak, 2008). The research presented in this thesis can be viewed as theory-oriented while it also aims to ensure practical relevance by providing insights for managers of manufacturing firms that are confronted with AM implementation decisions and managers of LSPs that assess AM as a potential threat for their traditional business models (see Section 1.3).

**Theory** is an essential element in theory-oriented research and can be defined as a "way of explaining observed patterns of associations between phenomena" (Bell et al., 2019, p. 19). Definitions of theory point to essential components of a theory. For example, Wacker (1998) operationalizes theory by referring to four components: definitions, domain of application, relationships, and predictive claims. Moreover, it is common to formalize theory in a set of propositions which specify the relationships between the phenomena or, more generally, between concepts. There is a broad spectrum of theory, for example, in terms of range, focus, and complexity (Van Maanen et al., 2007), starting from cases where the background literature acts as an equivalent to theory, all the way up to grand theories (Bell et al., 2019). Grand theories stand for broad ("all-inclusive"), high-level theoretical perspectives. They provide general theoretical frames as well as defined concepts and relationships at a high level of abstraction (Pellathy et al., 2018). As a result of this spectrum, there is a wide gap between grand theories and what Soltani et al. (2014, p. 1012) term "day-to-day research." To bridge this gap, Robert Merton was the first to refer to MRT – middle-range theory – in the context of social science (Merton, 1968). Today, MRT is the de facto standard in social science (Bailey, 1991). MRT approaches are specific since they are closely tied to an underlying context. They only operate in this application domain and, thereby, counter with their higher granularity and context-specificity the "traditional one size fits all" approaches of grand theories (Soltani et al., 2014, p. 1015). When theorizing at the middle range, the general theoretical models that provide global logics but limited specific insights into complex causal processes ("'black box' models") are used to illuminate theoretically grounded insights. These insights are applicable to a specific empirical context (Pellathy et al., 2018, p. 3). With that, MRT aims at achieving "theoretical contextualization," the balancing between the closeness to a specific context and grand theories (Craighead et al., 2016). Based on these characteristics, theorizing at the middle range is suitable for developing a deep inner understanding of how and why phenomena occur. By using realistic rather than abstract frameworks, MRT also provides the opportunity to develop relevant theories for both academia and practice. However, MRT also comes with the risk of falling short on one of the two contributions (Craighead et al., 2016; Soltani et al., 2014). Moreover, MRT is criticized for being vague and difficult to distinguish from non-MRT (Bailey, 1991).

In this thesis, the understanding of theory covers the full range, as described above. As one extreme, the existing background literature from the OSCM and business model research domain is used as an equivalent to theory to embed the findings in each of the four studies. Moreover, it serves to reveal contradicting and supporting arguments that can enrich and refine the existing state of the literature. On the other extreme, all-inclusive grand theories like the configuration theory (studies A.2 and B.2) are considered in order to discuss the findings in their light and to interpret and distill nuances of these theories. In addition, established concepts like the business model components (study A.2) are considered. They can serve as MRTs or as small-scale theories that are limited in the number of concepts presented as propositions, see Halldorsson et al. (2007). Table 3-1 demonstrates which grand, middle-range, and small-scale theories serve as the theoretical lenses for each of the four studies.

Table 3-1: Selected theoretical lenses for the four studies.

| Study | Grand theories | | | MRTs and small-scale theories | | |
|---|---|---|---|---|---|---|
| | TCE: Transaction cost economics | RBV: Resource-based view | Configuration theory | Nexus of business model dynamics and emerging technologies | Business model components | SCs as configurable systems (Fisher, 1997) |
| Study A.1 | | x (dynamic capabilities) | | x | | |
| Study A.2 | | | x | | x | |
| Study B.1 | x | x | | | | |
| Study B.2 | | | x | | | x |

The **grand theories** include TCE (transaction cost economics), the RBV (resource-based view), and the configuration theory. Note that these grand theories are "borrowed" from other disciplines, as is frequently done in the SCM community (Flynn et al., 2020). Such an approach is common since the SCM community lacks its own "socio-economic theoretical basis" (Halldorsson et al., 2007, p. 286). It is assessed as both a fruitful approach (Halldorsson et al., 2007) and a problematic one, since the theories may not be able to capture the idiosyncrasies of SCM (Flynn et al., 2020). In this thesis, TCE is borrowed from new institutional economics (Furubotn, 2001), the RBV from strategic management (Barney, 2001), and the configuration theory from its long history in organization science (Meyer et al., 1993). The following paragraphs provide introductions and justifications for the selection of the grand theories, starting with the combination of TCE and the RBV.

**TCE** contributes to the understanding of how firms draw their boundaries. Collectively termed as the "theory of the firm," firms must define their boundaries by deciding which activities to perform in-house or outsource via contractual arrangements to third parties (Tsay et al., 2018). Originally, the theory of the firm goes back to Coase (1937), who aims to explain why firms exist. Coase (1937, p. 390f) reasons that not only the price mechanism in assumingly efficient markets but "the costs of negotiating and concluding a separate contract for each exchange transaction which takes place on a market must also be taken into account." With that, Coase (1937) refers to transaction costs. He draws the conclusion that firms have the ability to reduce these costs in comparison to contracting on the market and argues that this is a reason for their emergence. Moreover, Coase (1937) establishes that there is a natural limit to a firm's growth; when the transaction costs within a firm (e.g., caused by overheads for organizing the transactions and losses due to mistakes) equal the transaction costs on the free market, a firm will tend to stop expanding (Coase, 1937). This initial work by Coase was taken up by Williamson. Both were awarded Nobel Prizes for their contributions and triggered the emergence of the major research stream of TCE in strategic management, economics, and beyond that scope (Macher & Richman, 2008). The core idea of TCE is that the choice of the organizational governance structure for transactions, hierarchy or market, is based on economic motives. It hence focuses on the efficiency of governance structures and postulates that the governance structure must be aligned with the attributes of transactions and aimed at minimizing the costs involved in carrying them out (Williamson, 1975). Transaction costs are expected to occur *ex-ante* and *ex-post* of a transaction between a buyer and seller (e.g., for searching and selecting a partner, negotiating, writing and enforcing contracts, and monitoring) (Tsay et al., 2018). Underlying assumptions of TCE are that decision-makers have a "bounded rationality" (i.e., they cannot fully specify all eventualities in contracts) and may behave opportunistically (i.e., acting in their self-interest) (Tsay et al., 2018; Williamson, 1979).

Since TCE focuses on the efficiency of the governance structure (Williamson, 1975) and aims to address the question of why firms exist (Coase, 1937), it keeps the firms' capabilities constant (Mayer & Salomon, 2006). The **RBV**, however, focuses on the question of why firms differ in their performance. This perspective emphasizes skills in value-creating activities instead of governance skills (McIvor, 2009). Moreover, the RBV applies knowledge-based reasoning instead of opportunism-based reasoning (Conner & Prahalad, 1996). According to Tsay et al. (2018), the long history of the RBV dates back to Penrose (1959), among others, but has mostly been credited to Barney (1991). The RBV assumes that firms have a heterogeneous resource base, including "all assets, capabilities, organizational processes, firm attributes, information, knowledge, etc." (Barney, 1991, p. 101). At its core, the RBV argues that a firm's sustained competitive advantage results from its individual and superior combination of resources. The RBV suggests attributes of resources that can generate a sustained competitive advantage, so-called VRIN-attributes (valuable, rare, imperfectly imitable, and non-substitutable) (Barney, 1991). These attributes were later developed to VRIO-attributes (valuable, rare, imperfectly imitable, and organization) (Barney, 1995). Relevant for this thesis is the extension of the RBV to dynamic markets to explain why certain firms have competitive advantages over others in light of rapid und unpredictable change, as is evident in the nascent AM market (Eisenhardt & Martin, 2000; Teece et al., 1997). **Dynamic capabilities** are a firm's abilities to align its internal resources with changes in the business environment. They enable firms to "achieve new resource configurations as markets emerge, collide, split, evolve, and die" (Eisenhardt & Martin, 2000, p. 1107). Eisenhardt and Martin (2000) emphasize that dynamic capabilities are idiosyncratic to a firm and may emerge from many starting points and on different paths, while for some dynamic capabilities "best practices" may also emerge. With such an understanding, strong dynamic capabilities are valuable since they can alter a firm's resource base. For this reason, they are recognized as a foundation for a sustained competitive advantage in a high-velocity context (Amit & Zott, 2016; Eisenhardt & Martin, 2000; Teece, 2018).

In combination, TCE and the RBV are coined as influential theories for investigating make-or-buy decisions and the resulting governance structures as their outcomes (McIvor, 2009). Indeed, TCE and the RBV are among the organizational theories that are recognized for their usefulness to "explain both structure and management issues of supply chains" (Halldorsson et al., 2007, p. 287). The theories take different perspectives on make-or-buy-decisions, and it is widely accepted that the combination of both theories enhances the understanding of such decisions (Holcomb & Hitt, 2007; Jacobides & Winter, 2005). Based on the combination of TCE and the RBV, hierarchical governance becomes not only a market failure caused by transaction inefficiency (via TCE) but also a firm's superior utilization of resources that the market cannot keep up with (via the RBV). Consequently, the decision for a specific governance structure is not solely based on transactional attributes but also on the attributes of a firm (knowledge, capabilities, etc.) leading to productivity advantages (Madhok, 2002). On this basis, TCE-based arguments may be suitable to explain the governance structure of specialized, repetitive activities such as manufacturing and logistics. The RBV, on the other hand, provides a framework for explaining the governance structure of more visible and potentially sensitive functions (Holcomb & Hitt, 2007), as is, for example, the case for the know-how-intensive AM design process. For these outlined reasons, **study B.1** applies the combination of TCE and the RBV to elaborate make-or-buy decisions for the specific case of industrial AM. In addition, **study A.1** relies on the RBV and, in particular, on the concept of dynamic capability for exploring AM-based business model dynamics of LSPs (see Table 3-1). The RBV is recognized for its infusion into the business model literature (DaSilva & Trkman, 2014). It basically assumes that a business model addresses and influences a firm's resources (Morris et al., 2005). Hence, with dynamic capabilities being manifested in a firm's abilities to align its internal resources with changes in the business environment, they also include the ability to align the business model with such changes (Teece et al., 1997). In this sense, Teece (2018) and Amit and Zott (2016) directly link business model change to the concept of dynamic capabilities. They emphasize that strong dynamic capabilities enable firms to proactively detect new opportunities and threats as well as to implement, test, refine, and revise business models. This understanding is established in Study A.1 to explore the path dependence of LSPs' resource base for responding to AM.

The **configuration theory** has traditionally been applied in organization theory (Ketchen et al., 2022). It aims at establishing organizational patterns or profiles (Flynn et al., 2010). Famous applications of configuration theory are, for example, the four types of firms of Miles and Snow (1978) and the five structural configurations of Mintzberg (1980). Originally, organizational literature mainly applied contingency theory, which investigates pairwise relationships. To overcome its limitations and investigate more complex relationships, the strength of configuration theory lies in its holistic perspective. It simultaneously considers multiple dimensions and complex, nonlinear interrelations while maintaining parsimony (Dess et al., 1993). In this vein, an organizational configuration is understood as "any multidimensional constellation of conceptually distinct characteristics that commonly occur together" (Meyer et al., 1993, p. 1175). Hence, configurations, also termed "gestalts," are characterized by their mutually supportive and often complementary elements (Miller, 1986, 2018). Such internally cohesive clusters of elements can be embodied in classifications in, for example, taxonomies or typologies (Stock et al., 2000). The variety of identifiable configurations is naturally limited since organizational elements fall into coherent patterns (Meyer et al., 1993). A key concept of contingency and configuration theory is the idea of the *fit*. It stems from the reasoning that effectiveness is high in organizations with "internal consistency, or fit, among the patterns of relevant contextual, structural, and strategic factors" (Doty et al., 1993, p. 1196). Note that the concept of fit requires both an internal consistency between a firm's structures and strategy as well as an external fit that is demanded by the firm's environment, for example, due to high degrees of change and unpredictability in technological development. Following the idea of the fit, firms that exhibit a fit, reflected in certain combinations of strategy, structure, and context, are expected to perform "better" than firms without such consistency (Stock et al., 2000).

Configuration theory is applied in this thesis in **study A.2** to develop generic business model configurations for LSPs in industrial AM SCs (see Table 3-1). This application domain of configuration theory is assessed by Zott and Amit (2009, p. 267) as a "useful starting point for developing measures of business model designs." They apply configuration theory to conceptualize and measure business model designs as a set of variables to capture the content, structure, and governance of transactions of business models (e.g., in their study Zott and Amit (2002)). In addition, **study B.2** makes use of the configuration theory to explore coherent SCD configuration for industrial AM (see Table 3-1). According to Ketchen et al. (2022), only a few SCM studies have applied configurational approaches so far (see, e.g., Cao et al., 2015; Flynn et al., 2010; Huo et al., 2015). Ketchen et al. (2022) propose that configurational theorizing offers value that has not fully been tapped compared to linear theory-building approaches in the SCM domain. Analog to Flynn et al. (2010), study B.2 establishes the understanding that changes in the external environment of a SC (e.g., the changes caused by AM in the technological environment) require a reaction. Hence, the development of strategies and the adaptation of SC structures to maintain fit to the external environment are necessary.

Finally, the applied **MRTs and small-scale theories** should briefly be mentioned (see Table 3-1). Study A.1 is based on the nexus of business model dynamics and emerging technologies, and study A.2 on the established business model components, as both are introduced in Section 2.2.1. Moreover, study B.2 understands SCs as configurable systems. This understanding has been established, in particular, for consumer SCs with respective product/demand characteristics and a strong customer focus, since the well-known work of Fisher (1997), as detailed in Section 2.3.1. The applied facets of theory displayed in this thesis bring up the question of the general role of theory in theory-oriented research, which will be discussed in light of this thesis next.

### 3.1.3 Relationships between theory and research in this thesis

The literature commonly distinguishes three relationships between theory and research for theory-oriented research: **deduction**, **induction**, and **abduction** (Spens & Kovács, 2006). These relationships will be explained and brought into the context of this thesis in this section. A deductive approach has a strong theoretical base. It is a theory-testing process of following the logic of moving from a general law (the theory) to a specific empirical case (Andreewsky & Bourcier, 2000). A deductive approach starts with established, general theory and derives logical *ex ante* hypotheses or propositions, which are then tested empirically to provide insights into whether the theory applies to a specific instance. Thereby, the generalization and discussion of the propositions and hypotheses generate the new knowledge (Spens & Kovács, 2006). An inductive approach mirrors this process (Johnson, 1996). It aims at developing instead of testing theory by starting with a specific empirical case and moving from this case to general theory (Andreewsky & Bourcier, 2000). Prior theoretical knowledge is optional. It can serve as a starting point for empirical observations, which lead to the formulation of *post hoc* hypotheses or propositions. New knowledge is developed by generalizing the hypotheses and propositions within a theoretical framework (Spens & Kovács, 2006).

Overall, deductive approaches are strongly favored across disciplines. However, in reality, there are multiple cases where research contains inductive and deductive elements and relies on an iterative process of going back and forth between data and theory. Therefore, the understanding of induction and deduction as tendencies and not as hard facts is advised by Bell et al. (2019). Moreover, deduction and induction face criticism: The linear approach of deduction is foremostly criticized for constraining the creativity in developing theories. Induction, on the other hand, assumes that enough empirical observations always enable theoretical generalization (Dubois & Gadde, 2002). To counter these disadvantages, abduction has gained increasing attention as a useful and fruitful approach for researchers that aim at discovering rather than confirming (Dubois & Gadde, 2014). Abduction is characterized by a "continuous interplay between concepts and data" taking place throughout the research process (Van Maanen et al., 2007, p. 1149). Previous theoretical knowledge plays an important role, for example, when theories are borrowed from other disciplines. Overall, the abductive approach is a creative, iterative process that continuously compares real-life observations with a theoretical framework ("theory matching") to suggest new hypotheses or propositions (Dubois & Gadde, 2002; Spens & Kovács, 2006; Van Maanen et al., 2007).

The facets in the relationship between theory and research (deductive, inductive, abductive) are associated with different **purposes in the theoretical knowledge generation process**: Inductive approaches commonly aim at contributing to theory building, deductive approaches to theory testing, and abductive approaches to theory elaboration. This differentiation is documented for case study research, for example, by Ketokivi and Choi (2014). According to Fisher and Aguinis (2017), the three purposes of theory building, theory testing, and theory elaboration can be understood as complementary. The decisive question for selecting one of them lies in the pre-existence of a theoretical and/or literature knowledge base. For instance, Ketokivi and Choi (2014, p. 238) formulate the following question at the starting point of their proposed decision tree for selecting one of the three purposes: "Do existing theories and literature provide sufficient basis for formulation of the research question?" Based on this existing theoretical knowledge base, different approaches may be selected as indicated in Table 3-2. Inductive theory building requires little or no pre-existing theory. It is suitable when exploring novel or unexplained phenomena in the case that existing theory/literature is scarce or not applicable. Typically, deductive theory testing requires an extensive theory/literature base to formulate the *a priori* hypotheses and test their underlying relationships in an empirical context. Hence, theory is emphasized compared to the empirical context to foster its further development (e.g., expansion or tightening). Lastly, abductive theory elaboration emphasizes both existing theory and an empirical context. Existing theory can explain a phenomenon partly. It is applied in a specific empirical context to derive a refined or elaborated theory that accounts for the empirical context (Fisher & Aguinis, 2017).

Table 3-2: Three purposes and their emphasis on theory and empirics (based on Ketokivi and Choi (2014)).

| Purpose | Theory-building research | Theory-testing research | Theory-elaborating research |
|---|---|---|---|
| Emphasis on existing theory | minor | major | medium |
| Emphasis on empirical context | major | minor | medium |

When discussing the relationships between theory and research in this thesis, it can be noted that inductive and abductive approaches dominate, as displayed in Figure 3-2. In addition, Figure 3-2 demonstrates the purpose and desired outcome for each study. Utterly **inductive approaches** can be found in the **studies A.2 und B.2**. Both studies are exploratory, aiming at developing generic business model configurations for LSPs (study A.2) and SCD configurations for industrial AM (study B.2). In line with an inductive approach, both studies contribute to theory building. In doing so, patterns emerge directly from the empirical data. Prior theoretical knowledge serves to sensitize and motivate the research objective, but it does not form the entry point into these exploratory studies. Moreover, it sets the ground for interpreting and discussing the findings, while the actual theorization is closely linked to the existing background literature and aims at enriching it (e.g., with supporting, more nuanced, or contradicting insights).

Deviating from the strong inductive character, **study B.1** demonstrates an **abductive approach** that aims at theory elaboration for investigating make-or-buy decisions for industrial AM. Study

B.1 theorizes at the middle range by analyzing how established arguments of TCE and the RBV as grand theories are modified in the context of emerging digital AM technologies. To be more specific, it applies a top-down MRT approach, according to Craighead et al. (2016). In doing so, study B.1 starts to navigate within the established relationships of the two theories and derives insights which are then substantiated with context-specific data so that the applicability of the theories can be discussed. Hence, study B.1 basically starts with a deduction and then goes back and forth between deduction and induction in a process of "theory matching," as is characteristic for abductive research approaches (Spens & Kovács, 2006). With its abductive approach and focus on theory elaboration, study B.1 responds to recent calls for the need for more MRT in the SCM (Craighead et al., 2016; Pellathy et al., 2018; Stank et al., 2017) and OM (Ketokivi, 2006; Soltani et al., 2014) communities. MRT approaches are promoted to increase the granularity of OSCM research by generating a limited, context-specific understanding of complex causal processes (Pellathy et al., 2018). In particular, MRT is assessed as valuable for investigating how the era of digital dominance, as represented by digital AM technologies in this thesis, alters established SCM models and frameworks (Stank et al., 2019).

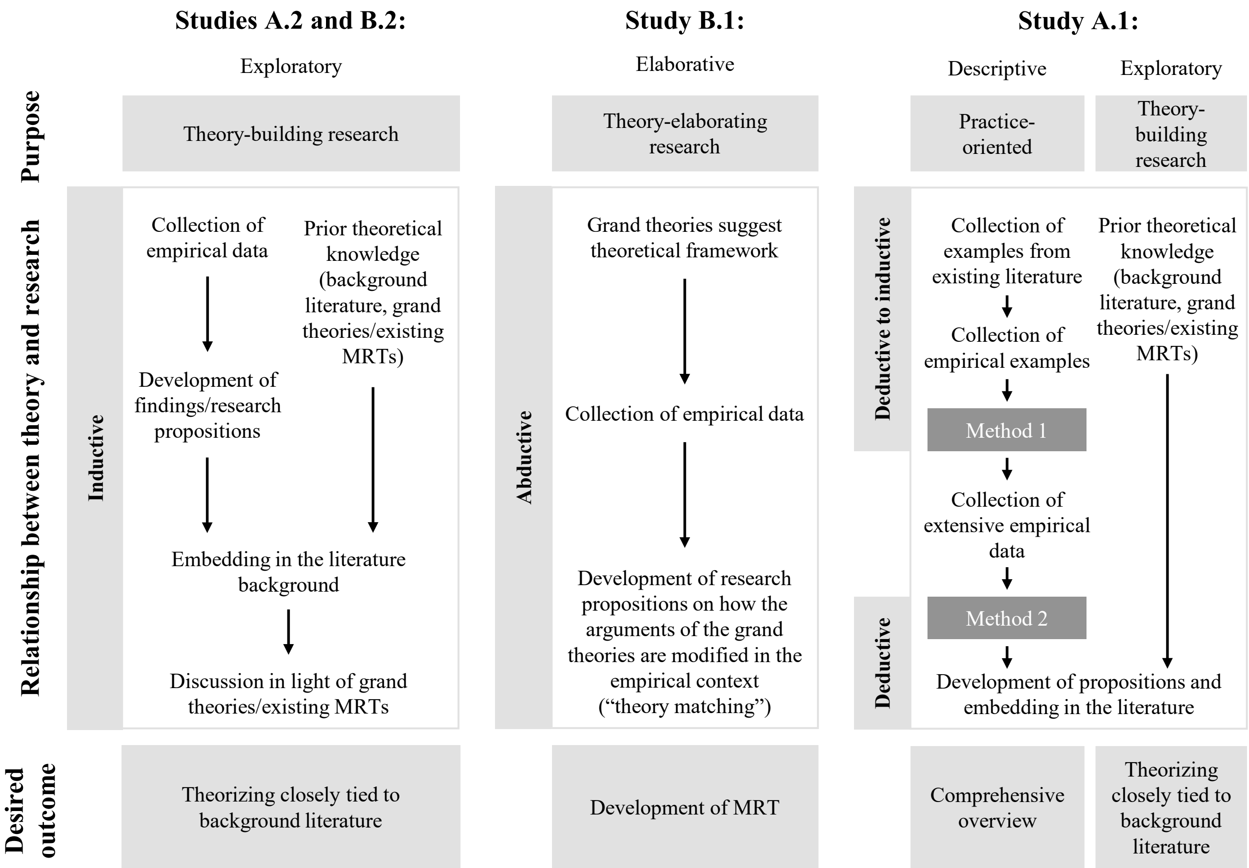



Figure 3-2: Relationships between theory and research in the four studies.

Finally, **study A.1** exhibits a **combination of multiple deductive and inductive tendencies** and, thereby, indicates that a strict commitment to one approach within one study is not always possible. This study applies a mixed-methods approach, consisting of a taxonomy development and a subsequent cluster analysis. The taxonomy development as the first applied method follows a conceptual-to-empirical approach, coined as the "classical strategy" of classifications (Bailey, 1994, p. 32). Based on this approach, the development of the taxonomy moves from deduction to induction (Bailey, 1994). The following collection of extensive empirical data is classified according to the taxonomy as a pre-defined (deductively formulated) classification scheme, and this is a prerequisite for performing the cluster analysis as a second method. Based on the multiple approaches, study A.1 also has multiple purposes and desired outcomes: On the one hand, study A.1 is practice-oriented and descriptive, which manifests in providing a comprehensive overview of AM activities. On the other hand, based on scarce existing literature and exploratory research questions, study A.1 aims to contribute to initial theory building on the reasoning for and interweaving of LSPs' AM activities for which prior theoretical knowledge (the RBV/dynamic capabilities as a grand theory) is considered.

This section has shown that the studies mostly follow inductive research approaches to contribute to theory building (studies A.2, B.2, and partly A.1). Theory elaboration is emphasized in study B.1 and tackled with an abductive approach. Theory testing, however, is not targeted in the four studies. Overall, Section 3.1 has established an understanding of theory in this thesis. The four studies have been positioned at the interface of OSCM and business model research and linked to underlying chains of argument from the strategic management literature. Moreover, awareness has been created for the use of grand theories and MRTs/small-scale theories in this thesis. This theoretical overview forms a suitable basis for concretizing the applied methodological approaches in the next section.

## 3.2 Methodological approaches

This section provides insights into the selected methodologies and their provided guidance. Starting with epistemological considerations in Section 3.2.1, the addressed causal processes and behavioral aspects of manufacturing firms and LSPs as decision-makers suggest interpreting this thesis from the perspective of social science. By committing to an interpretivist position and selecting primarily qualitative research methodologies that fit this position, Section 3.2.2 offers concrete insights into the applied qualitative research methodologies. With a focus on case study research and grounded theory, this section describes the phases of sample selection, data collection, and data analysis and clarifies how they are designed in the four studies.

### 3.2.1 Epistemological considerations

Overall, this thesis is concerned with strategic decision mechanisms and their outcomes with manufacturing firms and LSPs in the central roles of decision-makers. A strong focus lies on their behavior and the causal processes involved (*rationales*). Thereby, this thesis emphasizes the disciplines of OSCM and business model research from the perspective of **social science**. Basically, social science investigates human behavior and interactions. Together, social science and natural science, which studies the regularities in nature, are classified as empirically oriented "real" sciences, also termed factual sciences (Bunge, 1985). In contrast, formal sciences such as mathematics and computer science study formal systems independently of the reality (Radder, 1993). However, apart from this thesis, it should be noted that the OSCM and business model research are subject to further multidisciplinary influences. In particular, OM is closely linked to formal sciences since it makes use of methods (e.g., analytical modeling) from associated research fields like applied mathematics and statistics (Choi et al., 2016).

Following the philosophy of social science, the central concepts of a research design are the epistemology embedded in the theoretical perspective, the selected methodology, and concrete methods (Crotty, 1998). The term **epistemology** describes the theory of knowledge. It is based on ontological concerns that pursue the question of the nature of reality.[20] Epistemological considerations are necessary to ensure that the generated knowledge is sound. Two contrasting epistemological positions are commonly distinguished, which heavily influence the methodology and con-

[20] The ontological positions of objectivism and constructivism are particularly well known. Objectivism implies that social phenomena (e.g., organizations) have their own objective and external realities that are independent while constructivism understands social phenomena as socially constructed entities that are "made up" by humans (Bell et al. 2019).

crete methods chosen: the paradigms of positivism and interpretivism (Bell et al., 2019). Positivism assumes that the reality exists objectively, and humans are considered to be deterministic and reactive. Following this logic, data can be collected by directly observing or measuring phenomena. In doing so, a positivist position assumes that the approaches of natural science can be applied to social science. Hence, experimental research from natural science is mimicked, and findings are commonly considered to be context- and time-independent as well as value-free (Sachan & Datta, 2005). Contrary to this logic, interpretivism holds that the research objects of social science – humans and their interactions – differ significantly from the natural order. Interpretivism assumes that realities are constructed by the actions and understanding of humans. Findings are, therefore, context- and time-specific and idiographic (Sachan & Datta, 2005). While interpretivism aims at *understanding* human behavior, positivism is concerned with *explaining* human behavior. As a result, positivism advocates quantitative research approaches (e.g., surveys, experimental studies, and simulation), while interpretivism supports qualitative research approaches (e.g., case studies, grounded theory, and action research) (Mangan et al., 2004; Tashakkori & Teddlie, 1998). Moreover, epistemological considerations can be linked to the introduced relationships between theory and research (see Section 3.1.3). A deductive approach is typically associated with positivism and an inductive approach with interpretivism (Bell et al., 2019).

**Deductive positivism** is generally held to be the dominant research approach in management and organizational studies (Woiceshyn & Daellenbach, 2018), also in the OSCM community (Barratt et al., 2011), including logistics research (Mangan et al., 2004). This is reflected in the self-image of the overall OSCM research discipline: For example, Spens and Kovács (2006) found that inductive and abductive logistics research are often reported as being deductive. With such a perceived dominance, Aastrup and Halldórsson (2008, p. 749) claim that the discipline has maneuvered itself "into an intellectual blind spot." The positivist lens has direct implications for the research design, namely by providing the understanding that constructs like SCs are isolated, context-free, and "designable" systems within which managers act in predictable and aligned ways. This view enables researchers to produce solutions for improving or optimizing structures like SCs with deductive (e.g., mathematical) research methodologies (Adamides et al., 2012).

However, in the last two decades, several **SCM researchers** have criticized the dominant focus on explaining and "dictating" solutions and emphasized that there is a need for building an understanding (*how* and *why*) for observable phenomena (e.g., Näslund, 2002). They call for the consideration of the SC context, the distribution of power in the SC, and multiple perspectives (Sachan & Datta, 2005). Such considerations fuel the anti-positivist paradigms of inductive interpretivism and critical realism[21], which forms the middle ground between the two polar paradigms (Adamides et al., 2012). In this vein, SCM researchers stress the need for more behavioral research to complement quantitative research. They suggest the increasing application of qualitative and pluralistic research methods and methodological triangulation (e.g., combined qualitative and quantitative research designs) (Näslund, 2002).

Similar calls for an interpretivist lens and the resulting application of qualitative research, in particular case study research, can be observed among **OM researchers** throughout the years (e.g., Barratt et al., 2011; Flynn et al., 1990; Meredith, 1998; Singhal & Singhal, 2012). Pure qualitative research is still scarce in OM (Choi et al., 2016), but is in an ongoing process of growing acceptance and recognition for being more than "motivational" (Choi et al., 2016; Drejer et al., 2000). Raised arguments for qualitative research include its ability to address not only the physical ("hard") elements but also the relevance of human ("soft") elements in OM (Drejer et al., 2000; Voss et al.,

[21] Situated somewhere in the middle between positivism and interpretivism, critical realism has in common with positivism that the research design of natural science is assumed to be applicable to social science. At the same time, the realist position considers the existence of unobservables. However, the use of appropriate methods is expected to enable researchers to understand the reality (Godfrey & Hill, 1995).

2002). Furthermore, gaps between practitioners' needs and OM research are a well-reported problem (Slack et al., 2004; Sodhi & Tang, 2014). Qualitative research prevents such a detachment of OM research from practice and, thereby, contributes to closing the gaps. Moreover, developing sound and rich theory based on real-world conditions is seen as a prerequisite for analytical modeling and testing in a controlled environment, as is characteristic for quantitative research (Flynn et al., 1990; McCutcheon & Meredith, 1993).

Most of the research presented in this thesis takes an **interpretivist position**, following the proposed application of more qualitative and pluralistic research methodologies in the SCM and OM domain. Since this thesis aims at building an understanding of specific decision mechanisms and their outcomes, formalized in *how* and *why* research questions, a qualitative research design is a suitable choice that fits the nature of the problems and research objectives. Three studies (A.2, B.1, and B.2) focus on entirely qualitative research methodologies. They are based on the practices of grounded theory and case study research, as indicated in Table 3-3. As already mentioned, study A.1 differs from the other three studies in that it triangulates multiple methods. It applies a mixed-methods approach of qualitative and quantitative research methods, consisting of a taxonomy development and a subsequent cluster analysis. Both applied methods are weighted equally, reflecting their equal importance for answering the research questions of study A.1. With these characteristics, the applied mixed-methods approach can be classified as a "development" according to the proposed scheme for multi-methods research by Davis et al. (2011) and Tashakkori and Teddlie (1998). True to this classification as a "development," the taxonomy as the result of the first method is used as an input to classify a broad sample of empirically collected AM activities and perform a cluster analysis as the second method (Davis et al., 2011). Note that the classification of the broad sample of AM activities according to the taxonomy follows the methodological practices of qualitative content analysis. This makes a total of three qualitative research methodologies that are applied in the studies (see Table 3-3).

Table 3-3: Selected research methodologies for the four studies.

| Study | Qualitative research methodologies | | | Mixed-methods research (qualitative/quantitative) |
|---|---|---|---|---|
| | Grounded theory | Case study research | Qualitative content analysis | |
| Study A.1 | | | x | x |
| Study A.2 | x | | | |
| Study B.1 | | x | | |
| Study B.2 | | x | | |

Finally, the epistemological position of interpretivism and the resulting methodological choices in this thesis are reflected in light of the **theoretical purposes** (see Section 3.1.3). Theory building, as evident in the studies A.2 and B.2 and partly in study A.1, is a common purpose for qualitative research. In particular, grounded theory and inductive case study research are established as a means for theory building, as advocated by Corbin and Strauss (2015) and Eisenhardt (1989). As stated by Ketokivi and Choi (2014, p. 234), "The premise is that whenever theory does not exist, there is the option of generating it using empirical analysis." Moreover, Ketokivi and Choi (2014) argue for the position that case study research is also suitable for more diverse purposes. They propose case study research for abductive theory elaboration, as is applied in study B.1, and also for theory testing. However, the use of case study research for deductive theory testing has faced criticism, in particular from researchers with a positivist position, as highlighted by Barratt et al. (2011). To sum up this section, by following mostly an interpretivist position, this thesis primarily applies qualitative research approaches to contribute to theory building and theory elaboration. These qualitative methodologies will be explained next.

### 3.2.2 Selected qualitative research methodologies and resulting research designs

Qualitative research methodologies examine concepts in terms of words, talks, texts, and images from informants in order to build an understanding (Gephart, 2004). They are hence associated with the collection of non-numerical data, while quantitative research methodologies generally rely on numerical (quantifiable) data (Spens & Kovács, 2006). The resulting differences between **qualitative and quantitative research** are commonly contrasted: Qualitative research is based on open, flexible methods that can be changed and adapted throughout the process. Data is collected from a small and selected sample by researchers as the primary instrument, and the derived findings generally have a comprehensive and holistic character. Quantitative research, on the other hand, is associated with context independence, standardized methods, and large and random samples. Instruments are inanimate (e.g., questionnaires and computers), and the derived findings are typically more precise and narrower (Ketokivi & Choi, 2014; Smith, 1983). However, what seems like contrasting characteristics is oftentimes more blurred in practice than in theory since collected qualitative data is not necessarily only analyzed with qualitative methods and vice versa (Barratt et al., 2011; Pratt, 2009).

**Three characteristics** are noteworthy when defining what sets **qualitative research methodologies** apart: First, researchers collect broad and rich data not from their perspective but "from the perspective of those studied" (Pratt, 2009, p. 856). Hence, events and constructs are viewed through the eyes of informants (e.g., through interviewees) (Bell et al., 2019). Second, qualitative research does not rely on statistical generalization (e.g., like a survey) but on analytical generalization. Its objective lies in the generalization from the results to broader theory (Yin, 2014). Therefore, qualitative research lacks a "significance level" like a "'magic number' of interviews or observations" (Pratt, 2009, p. 856). Third, qualitative research is context-dependent by emphasizing the real-world context in which phenomena occur and not investigating them in isolation (e.g., in laboratory experiments) (Eisenhardt & Graebner, 2007).

Qualitative research encompasses diverse ways of collecting and analyzing data (Pratt, 2009). As motivated in Section 3.2.1, this thesis applies the methodological practices of **grounded theory** (study A.2), **case study research** (studies B.1 and B.2), and **qualitative content analysis** (study A.1). In a nutshell, grounded theory, as proposed in the 1960s by Glaser and Strauss (1967) and later by Strauss and Corbin (1998), follows a pure inductive logic for building theory. Grounded theory is an open-ended process that is entirely driven by the collected empirical data. This role of empirical data as the driving force literally enables the emergence of an empirically grounded theory (Corbin & Strauss, 1990). In comparison, case study research has continuously assessed such a "clean theoretical slate" as being unrealistic and impossible to achieve (Eisenhardt, 1989, p. 536). Multiple case study researchers have proposed a tentative *a priori* specification of constructs from existing literature to be able to shape an initial research design (e.g., Eisenhardt, 1989; McCutcheon & Meredith, 1993; Siggelkow, 2007). Thus, case study research suggests a more active use of existing literature and theory throughout the qualitative research process, as is also evident within this thesis. This is also reflected in the quest for pattern matching of empirically observed patterns with predicted or established patterns from previous studies (Eisenhardt, 1989), as realized in the discussion sections of all four studies. Overall, both case study research and qualitative content analysis, which provides guidance for text-based analysis, suggest more diverse (abductive and deductive) logics than pure inductive research (Ketokivi & Choi, 2014; Mayring, 2014; Voss et al., 2002).

The selected methodological guidance leads to specific procedures and requirements for the sample selection, data collection, and data analysis: First of all, qualitative research requires a clearly stated **unit of analysis** (Corbin & Strauss, 1990; Yin, 2014). This thesis explores abstract and socially constructed concepts like business models, strategic decisions, and SCDs. This entails that data cannot be directly collected from the units of analysis; separate units of data collection have to be defined. Indeed, Durach et al. (2017a) see it as an idiosyncrasy of SCM that data cannot be collected from SCs as units of analysis but from entities along SCs. Hence, Table 3-4 differs between the units of data collection and units of data analysis for each of the four studies.

The **sampling** of cases or, more generally, of the units of data collection is a thorough selection process in qualitative research. Corbin and Strauss (1990) propose the logic of "theoretical sampling," which implies that data and emerging categories in the data determine what and how much data to collect. For case study research, theoretical sampling is commonly recommended by applying "replication logic," that is, the selection of cases with predicted similar (literal replication) or contrasting (theoretical replication) results (Voss et al., 2002; Yin, 2014). In this thesis, replication logic is applied in the studies B.1 and B.2 to select polar/extreme cases and complemented with a snowballing approach[22]. In the other two studies, samples are purposively selected based on predefined criteria (study A.1) and based on the intention of maximizing the variety of perspectives (study A.2), see Table 3-4.

Table 3-4: Overview of the qualitative research designs in the four studies.

| | Qualitative content analysis | Grounded theory | Case study research | |
|---|---|---|---|---|
| | **Study A.1** | **Study A.2** | **Study B.1** | **Study B.2** |
| **Units of analysis** | AM activities of LSPs | Generic AM business model configurations for LSPs | Manufacturing firms as the actors that take AM make-or-buy decisions | AM SCD configurations |
| **Units of data collection** | LSPs, their partners, and third parties (that provide information on LSPs' AM activities) | LSPs, their potential partners/ competitors, and industrial customers in AM | Manufacturing firms (complemented with context-specific data from actors from the AM domain) | AM SC actors with a focus on focal manufacturing firms |
| **Sampling/selection of units of data collection** | Criterion sampling (websites), theoretical sampling (interviews) | Purposive sampling (maximized variety of perspectives) | Replication logic and snowball sampling | Replication logic and snowball sampling |
| **Data collection** | Websites and spotlight interviews | Interviews, internal documents, web searches | Interviews, internal documents, web searches | Interviews, internal documents, web searches |
| **Data analysis** | Coding according to the taxonomy (as a deductively formulated category system) | Open, axial, and selective coding; guidance by Gioia et al. (2013) | Open, axial, and selective coding; within- and cross-case analysis | Open, axial, and selective coding; use of the scheme by Gioia et al. (2013); within- and cross-case analysis |

Qualitative research methodologies recommend the **collection of data** from multiple sources, for example, interviews, direct observations, archival records, documents, and physical artifacts (Pratt, 2009). This thesis triangulates data from semi-structured interviews, internal documents, and websites. Table 3-4 provides an overview, while Figure 3-3 indicates the specific data sources. Study A.1 is primarily based on information collected from websites and enriched with spotlight inter-

[22] Snowballing describes the practice of asking interviewees to recommend other interviewees. This approach usually increases the number of interviewees, but it also requires attention (e.g., in terms of risk of bias) since interviewees are more likely to constitute a social network (Small, 2009).

views with LSPs. The studies A.2, B.1, and B.2 are all based on empirical data collected from interviews which are triangulated with internal data provided by some interviewees and information from web searches. However, the studies set different priorities. Study A.2 focuses on interviews with LSPs that are complemented with selected interviews with their potential partners/competitors and customers in industrial AM SCs, whereas the studies B.1 and B.2 focus on collecting insights from manufacturing firms. Study B.1 takes a firm-centric view on manufacturers as the dominant decision-makers in AM make-or-buy decisions. Additional data is collected from actors from the AM domain to develop a deep context-specific understanding of the industrial AM context, which is essential for the MRT approach of study B.1. Furthermore, the network perspective of study B.2 entails a focus on focal manufacturing firms, but also requires the collection of data from all typical actors of AM SCs to reflect manufacturing firms' viewpoints. It should be noted that due to the conceptual scope of this thesis, some of the data collected (mainly from interviews) were considered for multiple studies. The reasons for such overlaps lie, for example, in the dependence of LSPs on the perspective of manufacturing firms as their customers and the relevance of the outcomes of manufacturing firms' make-or-buy decisions for their implemented AM SCDs.

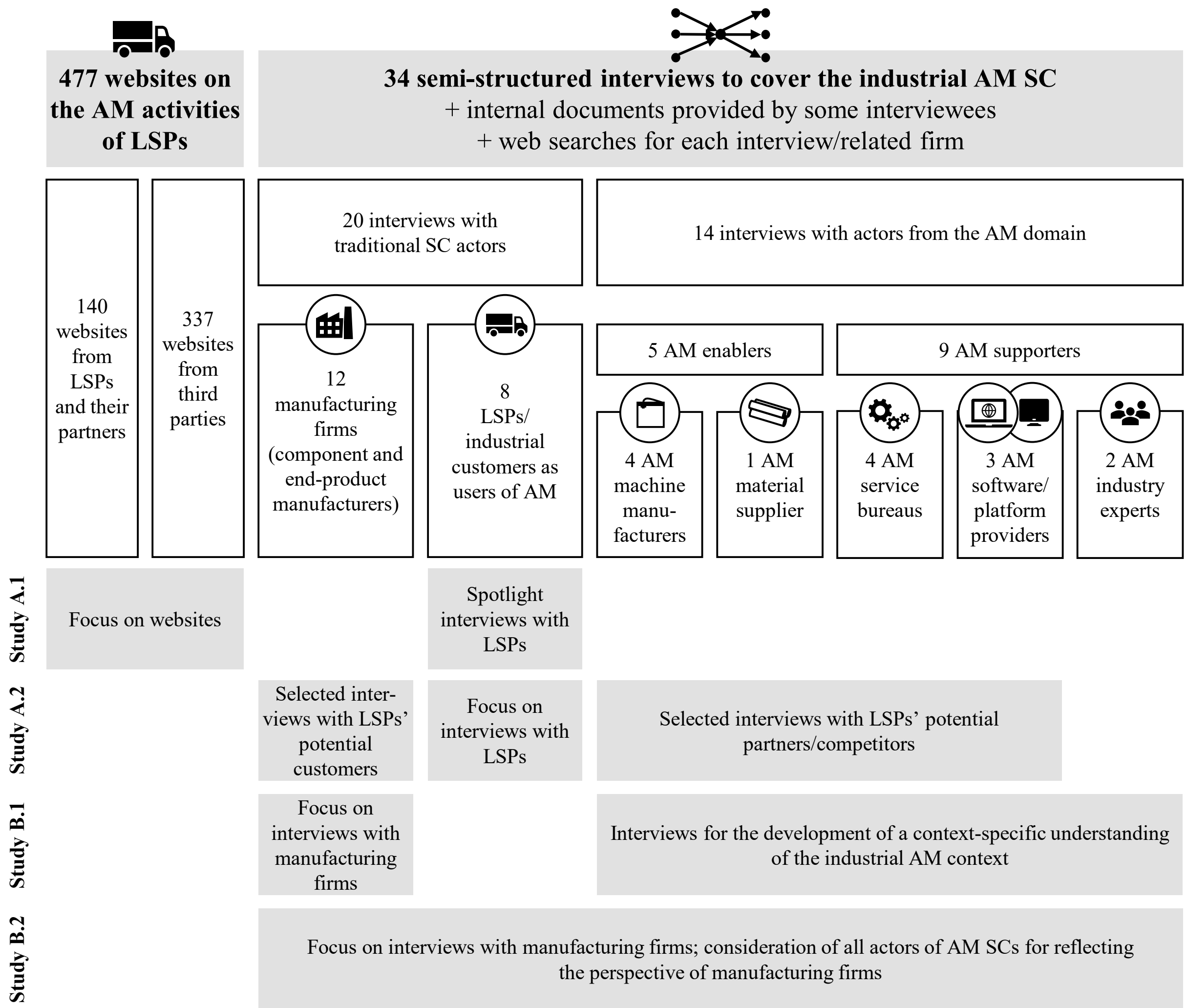



Figure 3-3: Data collected for the four studies.

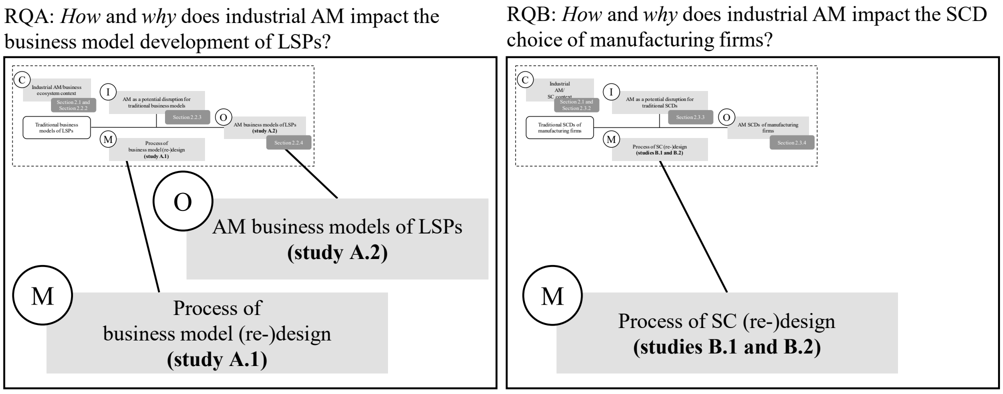
For the **data analysis**, grounded theory and case study research propose an interrelated process of data collection and analysis. Hence, data analysis starts directly with the collection of the first data and directs the further data collection in a process of "constant comparison" (Corbin & Strauss, 1990; Eisenhardt, 1989). Such an overlapping and flexible process was also pursued in this thesis. In three studies, the data analysis was based on the fundamental types of coding of grounded theory (open, axial, and selective coding), partly with a visualization of the emerging data structure with a scheme by Gioia et al. (2013) (study B.2). Only the coding in study A.1 followed a different approach by using the developed taxonomy as a deductively formulated category system. In addition, studies B.1 and B.2 followed the guidance provided by Eisenhardt (1989) in developing an understanding for each individual case (within-case analysis) before searching for patterns across the cases (cross-case analysis). Table 3-4 provides an overview of the research designs of the studies by highlighting the key choices for the sample selection, data collection, and data analysis.

## 3.3 Derived theoretical-methodological framework

Chapter 3 has built a theoretical and methodological foundation and classified the four studies accordingly. With that, it defines the theoretical and methodological scope of this thesis, analog to the conceptual scope in Chapter 2. Figure 3-4 uses the categories that have been applied to classify the four studies throughout Chapter 3. It summarizes the insights gained and, thereby, serves as a theoretical-methodological framework for addressing the overarching research questions RQA and RQB with the four studies in this thesis. Note that all insights gained aim to build an understanding of the *mechanism* (studies A.1, B.1, and B.2) and the *outcome* (study A.2) for LSPs' AM business model development and manufacturing firms' AM SCD choice when considering the CIMO-logic (Denyer et al., 2008).

Concerning the **use of theory** in this thesis, the following understanding has been established (see Figure 3-4): This thesis is positioned at the interface of OSCM and business model research. Hence, it touches on the embedded fields of SCM, OM, and LM research. Overall, it is based on the understanding that the addressed causal processes and strategic decisions (business model development and SCD choice) can contribute to firms achieving their competitive strategies and, hence, gaining and sustaining a competitive advantage in the era of digital AM. Moreover, the research presented can be primarily viewed as theory-oriented. It displays a broad understanding of theory, ranging from selected theoretical lenses from grand theories to established concepts (MRTs/small-scale theories) and to the use of the background literature as an equivalent to theory. The concrete studies within this thesis mostly apply inductive or abductive approaches with the purpose of contributing to theory building or theory elaboration. This is suitable to tackle the exploratory *how* and *why* research questions and to distill how the novel AM context changes established arguments from grand theories.

From a **methodological perspective**, the following chains of argument have been established (see Figure 3-4): The focus on causal processes and behavioral aspects in this thesis suggests interpreting the targeted research objective and underlying research questions through the lens of social science. From this perspective, the four studies mostly follow an interpretivist position that supports the application of qualitative research methodologies. Aligned with the interpretivist position, the studies are dominated by qualitative research approaches based on the methodological practices of grounded theory, case study research, and qualitative content analysis. Empirical data is collected from multiple sources (interviews, internal documents, and websites) and triangulated.




| Categorization | | Provided theoretical-methodological foundations: Studies A.1 and A.2 | Provided theoretical-methodological foundations: Studies B.1 and B.2 |
|---|---|---|---|
| Understanding of theory | Positioning of this thesis within research disciplines | ▪ Positioning in the **business model research** and **LM research**<br>▪ Established: Business models as a reflection of a firm's competitive strategies | ▪ Positioning in the **OM** and **SCM research**<br>▪ Established: SCs as structures that can contribute to firms achieving their competitive strategies |
| Understanding of theory | Selected theoretical lenses | Understanding of theory covers the full range:<br>▪ **Grand theories** (TCE, the RBV, and configuration theory)<br>▪ **MRTs/small-scale theories** (nexus of business model dynamics and emerging technologies, business model components, SCs as configurable systems)<br>▪ **Background literature** (embedding of the findings and enriching of the literature with the findings) | |
| Understanding of theory | Relationships between theory and research in this thesis | ▪ **Relationships between theory and research:** Dominance of inductive approaches (studies A.2 and B.2, partly study A.1) and abductive approaches (study B.1); minor relevance of deductive tendencies (study A.1)<br>▪ **Theoretical purposes:** Focus on theory building in three studies (studies A.1, A.2, and B.2); theory elaboration in study B.1 for developing MRT; no theory-testing emphasis in any study | |
| Methodological approaches | Epistemological considerations | ▪ Addressed inner causal mechanisms and behavioral aspects (*rationales*) suggest viewing the studies from the perspective of social science<br>▪ Positioning of this thesis with an **interpretivist lens**, which assumes that realities are constructed by the actions and understanding of humans and aims at understanding (and not explaining) human behavior<br>▪ Interpretivist position suggests the application of **qualitative research methodologies** | |
| Methodological approaches | Selected qualitative research methodologies and resulting research designs | ▪ **Mixed-methods research** (combination of qualitative and quantitative research) in study A.1 (based on data collected from websites and spotlight interviews)<br>▪ **Inductive qualitative research** that follows the methodological guidance of **grounded theory** in study A.2 (based on data collected from interviews, internal documents, and web searches) | ▪ **Abductive and inductive case study research** in studies B.1 and B.2 (based on data collected from interviews, internal documents, and web searches) |

Figure 3-4: Theoretical-methodological framework for the overarching research questions RQA and RQB.

Based on the established conceptual (Chapter 2) and theoretical-methodological (Chapter 3) foundations for the four studies, the main body of this thesis starts with part A, the studies A.1 and A.2, which focus on the AM business model development of LSPs. It is followed by part B, including the studies B.1 and B.2, which investigate the AM SCD choice from the perspective of focal manufacturing firms.

# Part A

## 4 Study A.1: How additive manufacturing drives business model change: The perspective of logistics service providers[23]

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**Publication details:** International Journal of Production Economics, Vol. 249, Article 108521. https://doi.org/10.1016/j.ijpe.2022.108521
**Status:** Published

**Abstract**

Additive manufacturing (AM) is expected to facilitate local manufacturing in shorter, less complex supply chains and, thus, impact the demand for traditional logistics services. With increasing dissemination, AM confronts logistics service providers (LSPs) with the question of how they should adapt their business model to the threats and opportunities that come with the emerging digital technologies. We structure the AM activities of LSPs and develop a deep understanding of their resulting business model dynamics. For this exploratory purpose, this study develops a taxonomy and performs a cluster analysis to present six clusters of how LSPs approach AM today. The six profiles include LSPs that reactively monitor AM or, in contrast, proactively leverage AM for their internal operations and the development of new services for their external customers. Among them, four profiles entail fundamental changes to the traditional business models of LSPs. We find that these LSPs oftentimes continue to rely on their traditional "analog" service strengths to offer integrated service bundles of AM and logistics solutions. They bridge their lack of specific resources by strategic alliances with AM experts. Only a few LSPs have started severing ties to their traditional businesses to develop digitally dominated, platform-based AM services that require different resources. Overall, the comprehensive picture of AM activities enables us to contribute to the knowledge of how LSPs navigate in the digital age and to the nexus of business model dynamics and emerging technologies. We propose a set of propositions and support practitioners in analyzing and designing AM activities.

**Keywords:** 3D printing, Logistics services, Business model dynamics, Digital supply chain, Taxonomy, Cluster analysis

### 4.1 Introduction

From a supply chain perspective, the essential game changer of additive manufacturing (AM) technologies lies in the digitalization of the manufacturing process. Parts are manufactured layer-by-layer directly from the digitally available product specification without product-dependent setup and tooling. This significantly reduces production setup time and upfront costs (Holmström et al., 2010). Several AM machines are even capable of simultaneously producing different parts (Olsen & Tomlin, 2020). With this inherent flexibility compared to traditional, tool-based manufacturing, AM fosters the shift from global, centralized supply chains to decentralized, small-scale manufacturing close to or even at the point of demand (Srai et al., 2016b). AM supply chains are expected to become shorter, less complex, and involve fewer actors (Durach et al., 2017b). Logistics service providers (LSPs) offer support and management services to ensure smooth operations in supply chains. Consequently, the dissemination of AM directly affects their business (Holmström & Partanen, 2014). Put simply, digital files travel easier than physical products (Verboeket & Krikke,

[23] The manuscript of the article has been slightly modified to ensure consistent format and style throughout this thesis. Note that the pronoun "we" is used in this chapter to refer to the authors of the article.

2019) and, thus, require less and different forms of handling. LSPs have recognized the threats and opportunities that come with AM and have started to tackle them.

A famous example is UPS, which has offered integrated, end-to-end AM and logistics solutions with in-store polymer 3D printing for consumers since 2013 (Berman, 2016). Today, we observe a decline from 62 to 20 listed UPS locations for 3D printing in the US (UPS, 2021). In addition, some LSPs use AM in their operations, most notably for spare parts provision by air carriers, including Air New Zealand, Emirates, and Etihad. By sourcing AM cabin parts (e.g., monitor frames, shrouds, and bumpers) from AM specialists or by building in-house production capacities for AM, these LSPs have started to replace traditional sourcing channels. AM is beneficial for these LSPs because small volumes of lightweight parts can be manufactured on-demand, reducing lead times and high inventory costs (Air New Zealand, 2018; Emirates, 2017; Etihad, 2019). Other LSPs monitor AM and assume a waiting position for now. For example, DHL has lowered its expectations for AM in its 2020 logistics trend radar. DHL predicts AM to complement (and not replace) traditional manufacturing and, thus, have a limited effect on the demand for logistics services (Deutsche Post, 2020).

The examples demonstrate a wide variety in LSPs' reactions to AM. Some LSPs may be in the process of creating new AM business models (e.g., UPS). In addition, LSPs may revise their internal operations and substitute traditional suppliers (e.g., Air New Zealand, Emirates, and Etihad) or may not expect AM to have a fundamental impact on their business yet (e.g., DHL). So far, the operations and supply chain management (OSCM) literature lacks an understanding of how and why traditional supply chain actors like LSPs respond differently to AM (Öberg et al., 2018; Savolainen & Collan, 2020a). Gaining such an understanding is fundamental for exploring the impact of AM on the existing business model of LSPs and the resulting interplay of AM activities and traditional logistics services. Moreover, it is an essential prerequisite for investigating the performance and organizational implications of LSPs' reactions to AM in future research. This study aims to fill this gap by considering a broad sample of LSPs and providing a structured overview of their responses to AM, both externally with new or adjusted business models and internally by adapting their operations. As our interest rests on capturing the current state of LSPs' AM activities, we focus on a process-based perspective. We address our objective in three research questions:

**RQ1:** *How* do LSPs respond to AM, that is, which specific AM activities of LSPs can we observe as a reaction to AM?

**RQ2:** What are the underlying reasons for LSPs to pursue these specific AM activities?

**RQ3:** *How* are the AM activities interwoven with the traditional business models of LSPs?

To investigate these exploratory research questions, we concentrate on LSPs that have already initiated their AM activities. We draw on the nexus of business model dynamics and emerging technologies as our theoretical lens and make use of arguments from the resource-based view (RBV), particularly related to dynamic capabilities. As suggested by Golicic and Davis (2012), we follow a mixed-methods approach that begins with a qualitative taxonomy development to structure AM activities of LSPs. Subsequently, we classify the AM activities of a selected sample of 47 LSPs based on the developed taxonomy. This classification uses data collected from publicly available sources and semi-structured interviews. We propose a six-cluster solution demonstrating distinct profiles for AM activities of LSPs via quantitative cluster analysis. We find one profile of LSPs that reactively follows information about AM (Monitors), two profiles that proactively leverage AM for their internal operations (Explorers and Co-Industrializers), and three profiles that proactively develop new services (Traditionalists, Complementors, and Intermediaries). On this basis, we explore the underlying reasons for these AM activities and demonstrate how AM entails fundamental changes in the traditional business models of four of the profiles.

The primary contribution of this study is a comprehensive picture and a profound understanding of the state of AM activities of LSPs, which we compile from public data sources and spotlight interviews. This structured overview of AM activities enriches the young stream of OSCM literature on AM business models. Furthermore, based on the analysis of the six derived profiles of LSPs, we contribute to building theory in two areas, summarized in a set of research propositions: First, we identify the specific reasons why LSPs respond to AM and, thus, build knowledge on why the service-based logistics industry adapts to AM. This relates to the literature dealing with LSPs' approach toward innovation and digital transformation (e.g., Busse & Wallenburg, 2011; Cichosz et al., 2020; Mathauer & Hofmann, 2019). The case of AM is of particular interest as it represents potentially disruptive emerging digital technologies. Thus, investigating LSPs' response to AM gives us valuable insights into how LSPs try to stay competitive in the era of digital supply chains (Goldsby & Zinn, 2016; Stank et al., 2019). Second, this study contributes to emerging technologies and business model dynamics in general (e.g., Baden-Fuller & Haefliger, 2013; Chesbrough, 2007) and in the AM context (Rong et al., 2018). Empirical investigations of business model dynamics are still scarce (Cavalcante, 2013). We show that although several LSPs have begun AM activities, their AM business models are not yet fully established. Furthermore, their AM business models heavily rely on their traditional services at the currently emerging stage of AM. LSPs enter strategic alliances with AM experts, compensating their skill and asset deficits, to cooperatively offer novel combinations of logistics and AM. Only a few LSPs decouple their AM activities from their traditional logistics services. Finally, we compile managerial implications. Among others, we provide insights for managers of LSPs in the design of new AM activities and the classification of their existing ones.

The remainder of this paper is structured as follows. Section 4.2 introduces the theoretical background for investigating the reaction of LSPs to AM. Section 4.3 details our combined approach of a taxonomy development and cluster analysis. In Section 4.4, we propose and analyze the six-cluster solution of AM activities of LSPs which contributes to answering RQ1. Section 4.5 discusses our findings in the broader context of LSPs' reasons for pursuing AM activities (RQ2) and business model dynamics (RQ3), summarized in a set of propositions. Section 4.6 presents our conclusions and suggests paths for future research.

## 4.2 Theoretical background

This study builds on the interplay of business model dynamics and emerging technologies. Section 4.2.1 introduces this theoretical lens for investigating AM activities of LSPs. Subsequently, Section 4.2.2 characterizes LSPs and their traditional business models before Section 4.2.3 builds an understanding of the literature-based expectations for AM activities of LSPs.

### 4.2.1 Business model dynamics in the context of emerging technologies

AM subsumes a set of digital manufacturing technologies, ranging from industrial AM for industrial-scale production to polymer 3D printing, commonly denoting the less demanding consumer side of the technologies (Thomas-Seale et al., 2018). Industrial AM uses AM machines for challenging metal and high-quality polymer applications such as new parts, spare parts, prototypes, and tools (Gartner, 2019). The recent ten-year market growth rate of 25.7% (2011–2020) demonstrates the immense growth potential of AM (Wohlers Associates, 2021b). The technologies are currently in an emerging stage and about to become early mainstream (Gartner, 2019). Following the definition of Hung and Chu (2006) for emerging technologies, AM technologies are recognized as core technologies, but they remain under development and have not yet demonstrated how they significantly affect competitive structures. More specifically, AM faces technological uncertainty as AM machines and materials evolve rapidly, the risk of obsolescence is high, and it is not clear which AM technologies will prevail. The AM market is a nascent one, and this early stage of formation constitutes a dynamic, unstructured setting with extreme ambiguity (Aldrich & Fiol, 1994;

Santos & Eisenhardt, 2009). It currently lacks industry standards and a clear-cut legal framework. Furthermore, competitive positions are not fully established, and relationships remain unstable.

This study focuses on how firms, as service providers, commercialize emerging technologies to turn them into valuable market offers (Rask & Günzel-Jensen, 2019) or, as users, leverage them in their operations (Chesbrough & Rosenbloom, 2002). We understand a business model as a "system-level, holistic approach to explain […] how firms do business" (Zott et al., 2011, p. 1019). The business model literature commonly refers to two central components of a business model (e.g., Amit & Zott, 2001; Casadesus-Masanell & Ricart, 2010): the value creation constitutes how a firm utilizes its resources to create and deliver value to the customer (Cachon, 2020), whereas the value capture describes the mechanism of generating incoming revenue flows from the value offered to the customer (Dubosson-Torbay et al., 2002). The value addressed in both components is embedded in the offerings of a firm, the value proposition (Chesbrough, 2010; Teece, 2018). Business scholars have shifted their emphasis from value capture to value creation (Zott et al., 2011), and this study follows this trend. Financial aspects as revenue models and cost structures should not be ignored. However, we experienced that they are not sufficiently transparent in publicly available information. Likewise, our interviewees were hesitant and mainly focused on identifying and evaluating value creation opportunities in AM. In line with our observations, the literature acknowledges that it is difficult to understand how value is captured from technologies like AM that have not yet matured (Despeisse et al., 2017a).

We want to explore the business model dynamics of LSPs, thus, understand how their traditional business models change in response to the emergence of AM. Emerging technologies are recognized as exogenous drivers that trigger or even necessitate business model dynamics (Baden-Fuller & Haefliger, 2013; de Reuver et al., 2009). However, changing existing business models is challenging (Chesbrough, 2010). Incumbent firms like LSPs rarely renew themselves completely but often rely on past investments and existing organizational structures to create permutations of existing business models (Teece, 2018). Building on this, Cavalcante et al. (2011) and Cavalcante (2013) propose how firms implement business model changes that start from their existing business models, including business model creations, extensions, revisions, and terminations.

Furthermore, incumbent firms may not recognize the threat of emerging technologies and, therefore, the need to adapt their existing business models. Hence, the literature advises them to undergo an exploratory process of trial-and-error learning and continuous business model adjustments (McGrath, 2010; Voelpel et al., 2004). For instance, Amit and Zott (2016) propose how firms should iteratively navigate through a cyclic, five-step business model design process of observing, synthesizing, generating, refining, and implementing. For such an ongoing process, firms need strong dynamic capabilities, which are their abilities to align internal resources, including their business model, to exogenous changes (Teece, 2018). Only with such abilities will they be able to detect new opportunities and threats proactively and alter their resource base as needed to respond to the exogenous changes. We refer to the RBV, which assumes that firms have heterogeneous resources, including all firm-owned assets, capabilities, and knowledge. It suggests that firms with a superior resource base are able to create and sustain a competitive advantage (Barney, 1995). With that in mind, strong dynamic capabilities become a tool or fundament for firms to build a competitive advantage that lies in the configuration of their resources (Eisenhardt & Martin, 2000).

### 4.2.2 Characteristics of logistics service providers

Logistics is a core business function, and it is vastly outsourced to specialists – LSPs (Langley et al., 2021; Zacharia et al., 2011). LSPs are organizations that manage, control, and carry out logistics services on behalf of their customers (Delfmann et al., 2002; Selviaridis & Spring, 2007; van Laarhoven et al., 2000). The industry is heterogeneous, with LSPs offering a wide range of services from basic logistics to the management and coordination of supply chains as an “orchestrator” (Carbone & Stone, 2005; Zacharia et al., 2011). We aim to include the full spectrum of LSPs and their specific AM activities and, therefore, differentiate between four types of LSPs: Standard LSPs, contract LSPs, consulting LSPs, and courier-, express-, parcel- (CEP) service providers.

Standard LSPs offer basic logistics services like transportation, warehousing, and transshipment services directly tied to their assets, such as their transportation fleets and locations (Sink et al., 1996). Their services are highly standardized, modular, and not adapted to specific customers (Hertz & Alfredsson, 2003). Examples of standard LSPs include carriers for air, rail, and road freight transportation and airport, port, and terminal operators (Stefansson, 2006). Contract LSPs, also termed third-party logistics (3PL) service providers, offer unique bundles of customized services with a long-term focus (Large et al., 2011; Prockl et al., 2012). For instance, the service bundles include value-added, management, information-related, and analytical services complementing basic logistics services (Stefansson, 2006). Accordingly, it is also common for contract LSPs to carry out light assembly and installation tasks originally allocated in the manufacturing domain (van Laarhoven et al., 2000). In contrast, consulting LSPs, also termed 4PL, commonly do not own any physical assets but subcontract those from contract LSPs (Büyüközkan et al., 2009; Win, 2008). In their role as relationship managers, consultants, and technology providers, they offer highly customized and comprehensive supply chain solutions (Hertz & Alfredsson, 2003). Finally, CEP service providers group LSPs that can deliver small, lightweight parcels quickly and accurately. The CEP sector is dominated by traditional actors, most notably by national post offices and established express providers (Ducret, 2014). Deviating from the above-introduced LSPs, CEP service providers cater to end consumers in addition to industrial customers (Dabidian et al., 2016).

The logistics market is a competitive one. To differentiate from competitors, many LSPs strive to prepare for their customers’ future needs through innovations (Flint et al., 2005). Leveraging technological advances and recognizing opportunities outside the traditional industry context is one element of logistics innovation. For instance, information and communication technologies have enabled LSPs to offer advanced shipment tracking services as an extension to the existing business model (Chapman et al., 2003). LSPs can access new technologies through the development of in-house resources and capabilities (make), purchasing the respective technologies from a supplier (buy), initiating strategic alliances (ally), or internalizing via a merger or acquisition (acquire) (Carbone & Stone, 2005; Mathauer & Hofmann, 2019).

### 4.2.3 Literature-based expectations for additive manufacturing and logistics services

The impact of AM on logistics services has not entirely manifested yet, and empirical validation is lacking (Boon & van Wee, 2018; Dong et al., 2021). However, the first paths can be identified. AM’s high resource efficiency of adding material layer-by-layer – compared to traditional subtractive manufacturing – leads to smaller transportation volumes and thereby reduces customers’ transportation needs (Barz et al., 2016b). Moreover, based on the inherently digital and flexible AM process, small-scale production close to the customers’ locations becomes a feasible option. The literature expects a reduction in the transportation and warehousing business from the resulting shift from centralized to decentralized manufacturing (Barz et al., 2016a; Eyers & Potter, 2015). Furthermore, AM may reduce the transportation of semi-finished products as AM allows for final production at one location (Khajavi et al., 2014). Additional transportation volumes, in turn, are likely to manifest in bulk transportation of raw materials and the last mile for decentrally manufactured finished products, where opportunities for pooling transportation are limited (Durach et al., 2017b; McKinnon, 2016; Rylands et al., 2016). In the global context, AM has the potential to marginalize the advantages of low-cost country sourcing based on its high automation (Chen, 2017; Durach et al., 2017b). The resulting reshoring of activities is expected to lead to shorter and less complex supply chains (Laplume et al., 2016; Verboeket & Krikke, 2019).

Based on the potential impact of AM, the OSCM literature argues that LSPs may develop new business models for AM to eventually balance losses in transportation and warehousing services (Chen, 2017; Hofmann & Osterwalder, 2017; Öberg, 2019). In this vein, Hecker (2021) proposes a methodology for LSPs to develop new services, using the AM service development as a use case. However, the insights into AM business models are limited (Holzmann et al., 2020a; Holzmann et al., 2020b), and Savolainen and Collan (2020a) point to a need for more tangible, case-based evidence in this domain. Visions for LSPs include that they could turn into manufacturers for AM (Durach et al., 2017b; Rehnberg & Ponte, 2018), such as by offering manufacturing services in their warehouses (Chen, 2017; Wieczorek, 2017; Zanoni et al., 2019), mobile AM in trucks (Ryan et al., 2017; Verboeket & Krikke, 2019), or local AM hubs close to the final consumers (Boon & van Wee, 2018; Öberg, 2019). These visions are based on the perception that the required competencies for the AM process are easy to acquire, making AM accessible for firms without manufacturing backgrounds like LSPs (Durach et al., 2017b) or retailers (Arbabian, 2022; Chen et al., 2021). Moreover, Holmström and Partanen (2014) envision LSPs to be in an ideal position to develop secure digital infrastructure for transferring the know-how-intensive digital product specifications to decentral AM machines. Similarly, Manners-Bell and Lyon (2012) and Pause and Marek (2019) picture LSPs in a consulting and managing role in AM, including decision support for the application of AM versus traditional manufacturing technologies, partner selection, and product life-cycle management. In addition, LSPs could offer transportation services specialized in raw materials for AM (Ben-Ner & Siemsen, 2017) and develop efficient logistics solutions for the last mile of AM end products in decentralized settings (Rauch et al., 2016; Rogers et al., 2016).

By proposing these visions, the extant OSCM literature postulates the static outcome of LSPs' business model dynamics, thus, complete business models that are expected to allow LSPs to create value in AM. In contrast to these static views, Rong et al. (2018) stress the need for a dynamic perspective on the process in which firms identify opportunities for value creation within the AM ecosystem. Since the late 1980s, the AM ecosystem has evolved, as outlined by Beltagui et al. (2020). It forms the context in which the AM activities of LSPs emerge and enables LSPs to access equipment, materials, and expertise for AM. In particular, specialized firms and startups have begun to offer AM machines, materials, and software and platform solutions (Ford & Despeisse, 2016; Rogers et al., 2016). Specialized service providers, commonly referred to as AM service bureaus, have grown the market to provide manufacturing and auxiliary services (e.g., (re-)design and consulting) for AM (Chaudhuri et al., 2019; Rogers et al., 2016). We follow Rong et al. (2018) by taking a process-based perspective and considering the context of the AM ecosystem when exploring how LSPs respond to AM, as presented next.

## 4.3 Taxonomic classification of additive manufacturing activities and cluster analysis

Section 4.3 details our methodological approach for exploring the reactions of LSPs to AM. This includes the taxonomy development and cluster analysis based on the sampling of LSPs, systematic data collection, and coding of their AM activities according to the taxonomy. Figure 4-1 provides an overview of our methodological approach and the structure of Section 4.3.

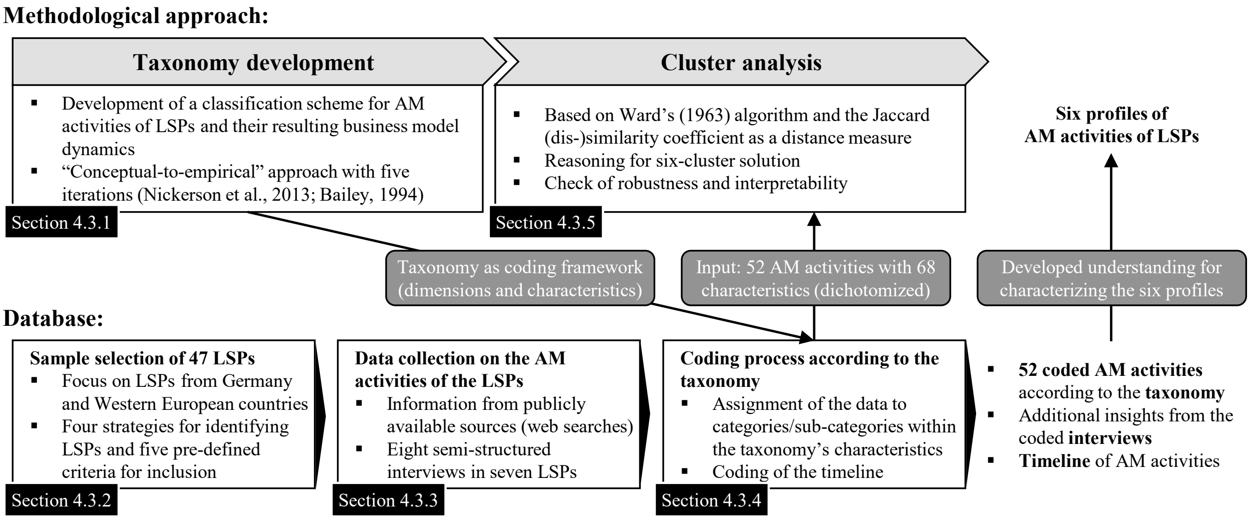



Figure 4-1: Overview of the methodological approach.

### 4.3.1 Taxonomy development

We developed a comprehensive taxonomy to differentiate and understand the nuances in the AM activities and resulting business model dynamics of LSPs. We use the term *taxonomy* in the understanding of Rich (1992) and Bailey (1994) as a "filling system" or "classification scheme" that supports us in structuring AM activities by coding and classifying them according to different characteristics. For the taxonomy development process, we opted to apply a *conceptual-to-empirical approach* as introduced by Nickerson et al. (2013). Such an approach is suitable for our study because the outlined theoretical lens and existing classifications from the OSCM literature on AM business models are adequate to conceptualize an initial taxonomy before using empirical examples to develop the taxonomy further. Moreover, such combinations of a deductive conceptual and following inductive empirical approach are commonly used in practice and, thus, termed the classical strategy of classification techniques (Bailey, 1994). In total, our taxonomy development process consisted of one conceptional iteration, three subsequent empirical iterations, and one test iteration. Appendix A details this process and specifies the selected conceptual and empirical sources for each iteration, strengthening the reliability of the proposed taxonomy development.

The resulting taxonomy of AM activities of LSPs is structured along five perspectives. Figure 4-2 provides an overview of the dimensions and characteristics within each perspective. The taxonomy covers how the AM activity relates to the traditional business model of the LSP (*business model dynamics*). It classifies the AM activity to an implementation stage and access strategy (*process-based perspective*) and displays the reasoning for the AM activity (*reasons of the LSP*). In addition, it provides a snapshot of how the LSP uses its AM activity to shape an AM business model for its external customers or – as a user – intends to create value for its internal demand (*aspired value proposition* and *aspired value creation*). Figure 4-2 further reveals each dimension's exclusiveness and initial development approach (conceptual/empirical) within the development process. The exclusiveness indicates if exactly one (=exclusive) or potentially multiple (=non-exclusive) characteristics may be observed for an AM activity per dimension.

Moreover, in the Supplementary Material A available for this study, we provide a description of the taxonomy and guidance for applying it to AM activities by demonstrating the criteria of fulfillment for each characteristic, illustrated with meaningful examples of LSPs.

| Perspective | Dimension | Characteristics | | | | | | | E/N | Approach |
|---|---|---|---|---|---|---|---|---|---|---|
| **Business model dynamics** | Change of the traditional business model | Creation | Extension | Revision | No fundamental change | | | | E | Conceptual (Cavalcante et al., 2011; Cavalcante, 2013) |
| | Interaction with the traditional business model | Based on existing assets/infrastructure | Based on existing services | Parallelization of an existing supply chain | Based on existing relationships to partner(s) | No relation to traditional business model | | | N | Empirical |
| | Interaction with traditional customers | Explicitly addresses existing customers | No connection to existing customers | | | | | | E | Empirical |
| **Process-based perspective** | Stage of the AM activity | Observe and monitor | Synthesize and generate | Implement | Run | | | | E | Conceptual (Amit & Zott, 2016; Teece, 2018) |
| | Access to AM | Make | Buy | Ally | Acquire | Pre-access | | | N | Conceptual (Carbone & Stone, 2005; Mathauer & Hofmann, 2019) |
| **Reasons of the LSP** | Motives for the AM activity | Organizational in-house learning | Learning from/with partners | Opportunity to take part in the digital transformation | Fear of consequences of AM for the traditional business | Response to market needs | | | N | Empirical |
| | LSP's functions in AM | Manufacturer | Intermediary | Integrator | Complementor | Co-industrializer | Innovator | Uninvolved | N | Conceptual (Pause & Marek, 2019) |
| **Aspired value proposition** | Addressed service for AM | Consulting | Design | Manufacturing | Certification | Selling of AM equipment | Logistics for AM | | N | Conceptual (Baumann & Roller, 2017; Bugdahn et al., 2018; Rayna et al., 2015; Rogers et al., 2016) |
| | Associated AM products | New parts | Spare parts | Prototypes and tools | AM equipment | | | | N | Empirical |
| | Targeted customers | Consumers (B2C) | Industry (B2B) | Internal demand | | | | | N | Empirical |
| | Unique advantage for customers | Reduced transportation and improved environmental performance | Improved spare parts service | All-in-one AM solution | Easy access to AM | Traditional logistics service | | | N | Empirical |
| **Aspired value creation** | Value-adding competencies | Manufacturing know-how | Transportation/inventory/ MRO know-how | Management of an ecosystem | Consulting/service know-how | | | | N | Conceptual (Pause & Marek, 2019) |
| | Value-adding assets | Logistics infrastructure and locations | Workshops/MRO facilities | AM machine/3D printer | Customer base | | | | N | Empirical |
| | Interaction with partner(s) | Firm(s) from the AM industry | Firm(s) from traditional industries | Academic partner(s) | No partner | | | | N | Conceptual (Holzmann et al., 2017; 2020a; 2020b) |
| | Function of partner(s) in AM | AM expert | Manufacturer | AM software or platform provider | AM hardware provider | R&D partner | No function | | N | Empirical |

E: Exclusive dimension (one characteristic observable at a time), N: Non-exclusive dimension (potentially multiple characteristics observable at a time)

Figure 4-2: Taxonomy of AM activities of LSPs.

## 4.3.2 Sample selection

We aimed to classify the AM activities of a broad sample of LSPs based on the developed taxonomy. For this purpose, we opted to focus on LSPs from Europe, mainly from Germany. This choice resulted from Germany's leading global position in the logistics sector (The World Bank, 2021), its competitiveness in the novel AM market (Wohlers Associates, 2021b), and practical reasons based on the authors' geographic affiliation. We iteratively applied four search strategies to identify LSPs that are active in AM, as detailed in Table 4-1. Potential LSPs were extracted from the member register of "Bundesvereinigung Logistik e. V.", an internationally recognized, German-based logistics association with more than 10,800 member firms (BVL, 2020), and checked for AM activities. Widespread AM news websites were systematically screened for notifications about LSPs. Likewise, we reviewed established AM industry events and industry networks for participating LSPs. Furthermore, we continuously used a snowballing approach, hence, followed up on references to AM activities of other LSPs mentioned but not directly published in the analyzed outlets. In this process of identifying LSPs, we applied five pre-defined criteria, which must all be fulfilled to include an identified LSP into our sample, as listed in Table 4-1. We successfully identified 47 LSPs that met the defined criteria by applying the different search strategies. Appendix B contains background information about the individual LSPs selected for the sample.

The sample includes 21 standard LSPs, 14 contract LSPs, four consulting LSPs, and eight CEP service providers, whereof five also provide postal services. Thus, it covers the full spectrum of different types of LSPs. Furthermore, our sample contains several of the largest European LSPs; only four LSPs are small and medium-sized enterprises (SMEs) (see Appendix B). This is far below the average in the transportation industry. For instance, 95% of German road freight transportation is operated by firms with less than 50 employees (BGL, 2020). Hence, the composition of our sample suggests that it is predominantly large LSPs that are active in AM. In terms of geographic affiliation, 49% of the LSPs have their headquarters in Germany, with Great Britain, France, and the Netherlands accounting for an additional 26%. The firms were founded between 1516 and 2011 and, thus, cover the spectrum from long-established to young LSPs. Based on the composition of our sample, our results foremostly draw a picture of how different types of larger Western European LSPs react to AM, entailing that these firms can directly take advantage of our results for progressing in their AM activities. By applying a sampling logic (criterion sampling) and detailing the empirical context (larger Western European LSPs), we foster the external validity of our approach.

Table 4-1: Strategies and criteria for sample selection.

| **Strategies for identifying LSPs:** | | |
|---|---|---|
| 1. | Logistics association | Extraction of LSPs from the member register of Germany's major logistics association "Bundesvereinigung Logistik e. V." and subsequent web searches to identify LSPs that pursue AM activities; search syntax: ("name of the LSP") AND ("additive manufacturing" OR "3D printing" OR "3D-Druck") |
| 2. | AM industry websites | Search for announcements and reports about LSPs on two relevant AM industry news websites with a wide scope of coverage (https://3dprintingindustry.com and https://www.3druck.com) |
| 3. | AM industry events and networks | Search for LSPs on lists of participants of two AM industry events (the annual "Additive Manufacturing Forum" and the exhibition "Formnext") and lists of members of two AM industry networks ("MGA Mobility - MGA Medical - Mobility goes Additive e. V." and "Verband 3D-Druck e. V.") |
| 4. | Snowball sampling | Follow up on any indications of AM activity of other LSPs identified during the application of strategies 1 to 3; search syntax: ("name of the LSP") AND ("additive manufacturing" OR "3D printing" OR "3D-Druck") |

*Table 4-1 continued.*

| Criteria for inclusion of LSPs into the sample: | | |
|---|---|---|
| 1. | Business model | The firm's traditional business model meets the LSP definition as introduced in Section 4.2.2 |
| 2. | Civilian industry | The LSP operates in civilian industry and, thus, does not provide military logistics services |
| 3. | Geographic affiliation | The headquarters of the LSP is based in Europe |
| 4. | AM activity | The LSP is active in AM, at least actively observing the AM market; a fully rolled-out AM business model is not a prerequisite |
| 5. | Available information | Information about the AM activity of the LSP is available in English or German and is adequate (detailed and comprehensive) to analyze the activity |

### 4.3.3 Data collection

We extensively collected data on the AM activities of the 47 LSPs via web searches and spotlight interviews with selected LSPs. The overall data collection process overlapped with the data analysis. Combined, they took place between March 2019 and February 2021.

The web searches aimed at collecting publicly available data that are adequate to track the history and develop an understanding of the individual AM activities of each LSP. Table 4-2 specifies the search syntax, search mode, analysis of search results, and data storing process that we applied for each LSP. Publicly available data were used because they are easily accessible, available in considerable volumes, and independent of the research objective (Rabinovich & Cheon, 2011). We prioritized collecting data provided directly by the LSPs and their partners for their AM activities (e.g., via the firms' websites, press releases, and published reports) and complemented the obtained information with data from third parties (e.g., online articles, industry reports, and interviews with LSPs). In this process, we evaluated the quality of the websites from third parties against common criteria (Aladwani & Palvia, 2002); see Table 4-2. By conducting full-text screenings, we assessed the contribution of each additional website to the understanding of the LSP's AM activities, starting with the websites from LSPs and their partners. The data collection per LSP was terminated with achieved saturation, indicating that new data will likely provide no or marginal new insights into the LSP's AM activities, as detailed in Table 4-2. In total, we collected 477 websites that we stored in MAXQDA for systematic coding. The LSPs and their partners provided 140 websites directly; 337 are from third parties. To increase the reliability of our study, the Supplementary Material B specifies each of the 477 websites and provides an analysis of the sources.

The described data collection strategy relies on information that the LSPs have chosen to communicate publicly about their AM activities. Thus, it may well be filtered to report positive messages and marketing communication toward potential customers. To counter this bias and enhance the construct validity of our approach, we opted to triangulate the data from public sources with primary data collected in semi-structured interviews. We arranged eight in-depth interviews with interviewees from seven large LSPs with rather advanced AM activities from our sample, including four standard LSPs and three contract LSPs. Our interviewees were in management positions and, therefore, able to assume a strategic perspective on their firms' AM activities and related business model dynamics. Moreover, they had already gained first-hand experience in the emerging AM market.

Table 4-2 summarizes how we established contacts and prepared for the interviews. It further details the interview mode and the data storing process. In addition, Appendix C clarifies the circumstances of each interview (e.g., the interview type, duration, and interviewees' job positions). As outlined in Table 4-2, we followed the identical approach for each interview, including the use of a semi-structured interview protocol (see Appendix C) and a standardized data collection and storing process (i.e., recording, transcription, content verification, revision) to increase the reliability of our collected interview data.

Table 4-2: Data collection process.

| **1. Collection of publicly available information via web searches:** | |
|---|---|
| Search syntax | (“name of the LSP”) AND (“additive manufacturing” OR “3D printing” OR “3D-Druck”) |
| Search mode | ▪ Web searches: search engine “Google”; web browser “Google Chrome”<br>▪ Prioritization of websites from LSPs/partners; complementation with third parties<br>▪ Last revision and update of the collected websites in February 2021 |
| Analysis of websites | ▪ Quality assessment of the websites from third parties according to Aladwani and Palvia (2002) and rejection of websites with perceived low quality:<br>– Appearance (focus on the proper use of language and graphics-text balance)<br>– Technical adequacy (focus on availability, navigation, valid links, security)<br>– Content quality (focus on consistency and completeness)<br>– Availability of specific content (focus on imprint/contact details, policies)<br>▪ Full-text screening of the websites<br>▪ Termination: Adding of new websites to the database until the saturation of the obtained information is likely (pre-defined criterion: no new insights into the AM activity of the LSP are gained with three consecutive websites) |
| Data storing process | ▪ Storing of the websites via the “Web Collector” of MAXQDA; import to MAXQDA<br>▪ 477 documents in total; 10.1 documents on average per LSP |
| **2. Collection of primary data via semi-structured interviews:** | |
| Establishment of contacts and preparation | ▪ Development of a semi-structured interview protocol focusing on the AM activities and resulting business model dynamics of LSPs (see Appendix C)<br>▪ Contacting potential candidates via email and/or telephone<br>▪ Decline of the invitation to participate in our study by several LSPs, including all approached consulting LSPs and CEP service providers; partly based on the early stage of their AM activities<br>▪ Sending of a letter of introduction with a description of the general topic, an introduction to the research team, and organizational details |
| Interview mode | ▪ Interviews per LSP: one interview per LSP (exception: one standard LSP with two interviews)<br>▪ Interview type: four face-to-face interviews, four interviews via telephone/video<br>▪ Interview duration: between 37 and 67 minutes; on average 51 minutes<br>▪ Number of interviewers: two interviews with two authors to increase the conformity of interview techniques; six interviews with one author present<br>▪ Number of interviewees: one or two interviewees per interview |
| Data storage process | ▪ Recording of the interviews<br>▪ Full transcription by the authors resulted in 117 single-spaced pages<br>▪ Sending of the transcripts to the interviewees for content verification<br>▪ Revision by the authors and storing in MAXQDA |

### 4.3.4 Data analysis

Coding was conducted in MAXQDA as a common database for both the 477 stored websites and 117 single-spaced pages of interview transcripts. We applied qualitative content analysis according to Mayring (2014) for coding the AM activities of the LSPs. For this purpose, the dimensions and characteristics of the taxonomy served as a deductively formulated category system. Sentences were defined as the coding unit and assigned to the characteristics of the taxonomy. As the coding progressed, we started to develop a data structure for each characteristic of the taxonomy. Thus, we searched for similar codes within our pre-defined characteristics and successively grouped them into categories and sub-categories to distill patterns of similar AM activities. Overall, the data structure was developed in a two-step process consisting of a tentative run-through and a revision in a second iteration for evaluating and refining the coding. During this process, we positioned our findings in the extant literature (see Section 4.2), as we will discuss in Section 4.5.1 and Section 4.5.2. This matching of our empirically observed patterns with previous studies is a means to ensure internal validity. Moreover, the authors intensively discussed exemplary codes and the emerging patterns in the data structure. Conflicts between the authors were resolved to create a common understanding for the AM activities of each LSP, as suggested by Mayring (2014). Based on this consensus, the full coding process was conducted by one of the authors.

The data analysis revealed that five LSPs pursue two disjunct sets of AM activities, which lead to different business model dynamics. For this reason, we opted to code these AM activities separately, resulting in a total of 52 coded AM activities by 47 LSPs. Moreover, it emerged as a natural consequence – given our process-based perspective – that our sample includes LSPs with early-stage AM activities. These LSPs do not have fully established value propositions and value creation mechanisms yet. Consequently, for these LSPs, we did not observe all characteristics for these domains. This affected specific dimensions of the two perspectives *aspired value proposition* and *aspired value creation*. The shares of dimensions with unobservable characteristics range from 13% (for *addressed service for AM*) to 29% (for *value-adding assets*). However, as including LSPs at all stages of their AM activities provides insights in itself, we intentionally did not recode these observations and retained them in the dataset for analysis. Being aware of this structure in our data is one reason for basing our cluster analysis on the Jaccard coefficient (see Section 4.3.5). To account for our process-based perspective, we also coded the AM activities timeline for each LSP by extracting dates and related events from our data. Note that terminations of AM activities were also coded but are more difficult to identify due to lower volumes of public communication for these events. Such information asymmetry entails a selection bias for the considered events (Sorescu et al., 2017) that we could not fully avoid in this study.

In summary, the coding process resulted in a profound understanding of how each AM activity from our sample of LSPs is classified within the existing taxonomy. The interviews significantly enriched the publicly available data and particularly fostered our understanding of LSPs' reasons for selecting specific AM activities (i.e., the taxonomy's dimensions *motives for the AM activity* and *LSP's functions in AM*). Note that the interviewees not only shared insights into their realized AM activities but also their opinions about various possible AM activities and future expectations for the position of LSPs in the AM market. Thus, the interview data has an overarching character compared to the coded websites that provide insights into specific AM activities of specific LSPs.

### 4.3.5 Clustering procedure

We opted to conduct a cluster analysis that enabled us to group the LSPs and their AM activities according to their similarities into comparatively homogeneous subsets (Aldenderfer & Blashfield, 1984). As a prerequisite for the cluster analysis, we dichotomized the 52 AM activities by assigning to each characteristic of the taxonomy the value of 1 if it is present and 0 for its absence. Subsequently, we aimed to increase the reliability of the cluster analysis by first checking for constant, non-decisive characteristics (Backhaus et al., 2016). Second, we investigated the effects of three highly correlated characteristics (Ketchen & Shook, 1996).[24] By iteratively comparing cluster solutions of the dataset with removed correlations and the initial one, we found that the three highly correlated characteristics do not overemphasize the information they provide. They have a limited effect on the cluster solution by slightly enhancing the difference between two clusters described as Intermediaries and Complementors in Section 4.4. Thus, we did not perceive it as necessary to remove the three highly correlated characteristics from our dataset. Third, we ruled out the possibility of having outliers in the dataset by using a single-linkage clustering algorithm and analyzing the resulting dendrogram (Backhaus et al., 2016; Li, 2005). In total, the data preparation resulted in a matrix of 52 observations (AM activities) with binary values for 68 characteristics.

[24] The correlations were identified by calculating Cramér's V based on Pearson's chi-squared test of independence. We found Cramér's V $>0.9$ for three highly correlated characteristics: (1.) Interaction with traditional customers → *No connection to existing customers*, (2.) Value-adding resources → *AM machine/3D printer*, (3.) Function of partner(s) in AM → *No function*.

Subsequently, we conducted the cluster analysis using R 4.0.3. We decided to apply Ward's (1963) algorithm, a hierarchical agglomerative clustering approach. It generates solutions for all possible numbers of clusters and, therefore, serves well for the exploratory purpose of our study (Ketchen & Shook, 1996). Furthermore, Ward's (1963) algorithm is commonly applied in strategy research (Ketchen & Shook, 1996), for practical applications (Gimpel et al., 2018), and performs well for our expectation of clusters with similar sizes and no outliers (Ferreira & Hitchcock, 2009). We selected the Jaccard (dis-)similarity coefficient among the distance measures suitable for binary data (Li, 2005, 2006). For our analysis, we considered two AM activities as similar if similar characteristics are present (coded as (1,1) in our data). In other words, similarity stems from observable characteristics, but the absence of characteristics (coded as (0,0)) cannot establish similarity between two AM activities as this can result from different reasons (e.g., early-stage AM activities as outlined in Section 4.3.4). Thus, the Jaccard coefficient is suitable for our data structure, as it does not consider the non-existence of characteristics (0,0) in assessing similarity (Finch, 2005).

After applying Ward's (1963) algorithm, we aimed for a cluster solution that is well interpretable and demonstrates utility (Backhaus et al., 2016; Punj & Stewart, 1983) for our understanding of the AM activities of LSPs. We considered common measures in this iterative process. For instance, the elbow criterion (Backhaus et al., 2016; Ketchen & Shook, 1996) suggests a three-cluster solution. This three-cluster solution is displayed in the first, higher-level branching that we will introduce with Figure 4-4 in the next section. However, we realized that this solution does not provide sufficient managerial details to analyze the nuances in the AM activities of LSPs. Hence, we further split clusters until we reached a six-cluster solution that appeared to be a suitable compromise in terms of the level of detail and interpretability. Appendix D demonstrates how the 52 AM activities are assigned to the six clusters and illustrates the relative frequencies within the taxonomy for each cluster.

To check the robustness of this allocation based on the Jaccard distance metric, we applied a partitioning clustering algorithm to the given number of six clusters as recommended by Punj and Stewart (1983) and Ketchen and Shook (1996). K-modes algorithm was selected for its applicability to categorial data (Huang, 1997). Despite the underlying distance measure of the k-modes algorithm being less suitable for our dataset, it essentially confirmed our cluster solution by 85%. Eight suggestions for reassigning AM activities based on the k-modes algorithm were individually evaluated and rejected as they did not increase the interpretability of the clusters. In addition, we created contingency tables and used Pearson's chi-squared test of independence to investigate the dependence between the six clusters and each dimension of the taxonomy (see Appendix E). The derived p-values suggest stochastic dependence between the six clusters and each dimension ($p$-value $\leq 0.05$). Hence, all dimensions influence the allocation of AM activities in the six clusters. By calculating Cramér's V based on Pearson's chi-squared test, we gained additional insights into the association between the clusters and dimensions (Cramér, 1946). Cramér's V varies from zero (no association) to one (complete association). We found high associations (Cramér's $V > 0.8$) between the six clusters and three dimensions of the taxonomy, the *change of the traditional business model*, *interaction with traditional customers*, and *LSP's functions in AM* (see Appendix E). These results indicate that the three dimensions contribute most to the emergence of the six-cluster solution. Thus, we will focus on these dimensions in the following characterization of the clusters.

## 4.4 Six profiles for additive manufacturing activities of logistics service providers

In this section, we structure the findings that emerged from the data analysis and clustering procedure to address RQ1, hence, how LSPs respond to AM with specific AM activities. On a timeline, we found first AM activities in our sample of 47 selected LSPs in 2013, marking the peak of hype surrounding consumer 3D printing (Gartner, 2014). At that time, the expiration of key patents for multiple AM processes caused price drops and made industrial AM machines and polymer 3D printers more accessible for firms and private households (Beltagui et al., 2020; Gibson et al., 2015). From this moment on, we recorded steadily growing AM activities of the standard LSPs and contract LSPs from our sample. In contrast, consulting LSPs demonstrated occasional activities and CEP service providers a fairly constant involvement in AM. Most LSPs from the sample (70%) were active in AM in 2020. Figure 4-3 depicts the cumulated timelines of the identified AM activities.

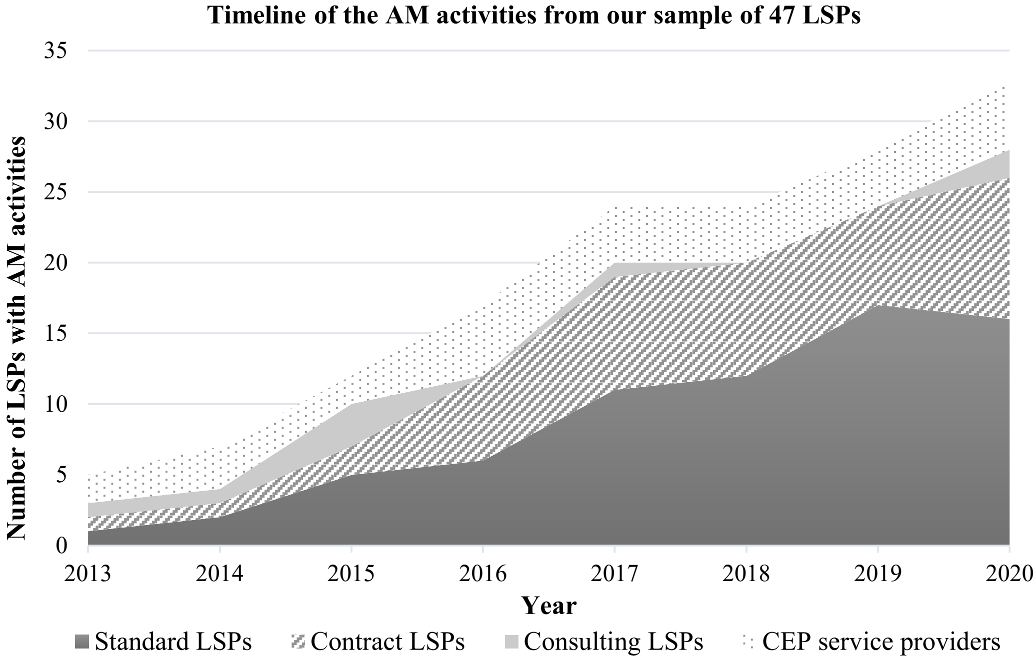



Figure 4-3: Timeline of the identified AM activities.

By applying the described clustering procedure to the 52 AM activities, we arrived at six clusters characterizing the patterns of distinct AM activities of LSPs and resulting business model dynamics: *Monitors*, *Explorers*, *Co-Industrializers*, *Traditionalists*, *Complementors*, and *Intermediaries*. Figure 4-4 replicates the information obtained from the dendrogram to demonstrate how the six clusters emerged from three branches. The first branch contains LSPs with reactive AM activities (n=10), which we refer to as Monitors, that currently observe AM and hesitate to intensify their involvement. In contrast, the other two branches comprise proactively initiated AM activities. These LSPs use the emerging digital technologies as users for their operations (n=20) and the development of new AM services for their external customers (n=22). Users branch further into Explorers and Co-Industrializers, and new AM services into Traditionalists, Complementors, and Intermediaries. The following characterizes the profiles individually along the three branches, underpinned with representative quotes from publicly available sources and our interviews. Additional quotes are provided in Appendix F to enrich the characterization of the clusters. The interviews are not exclusively assigned to specific clusters due to their overarching nature.

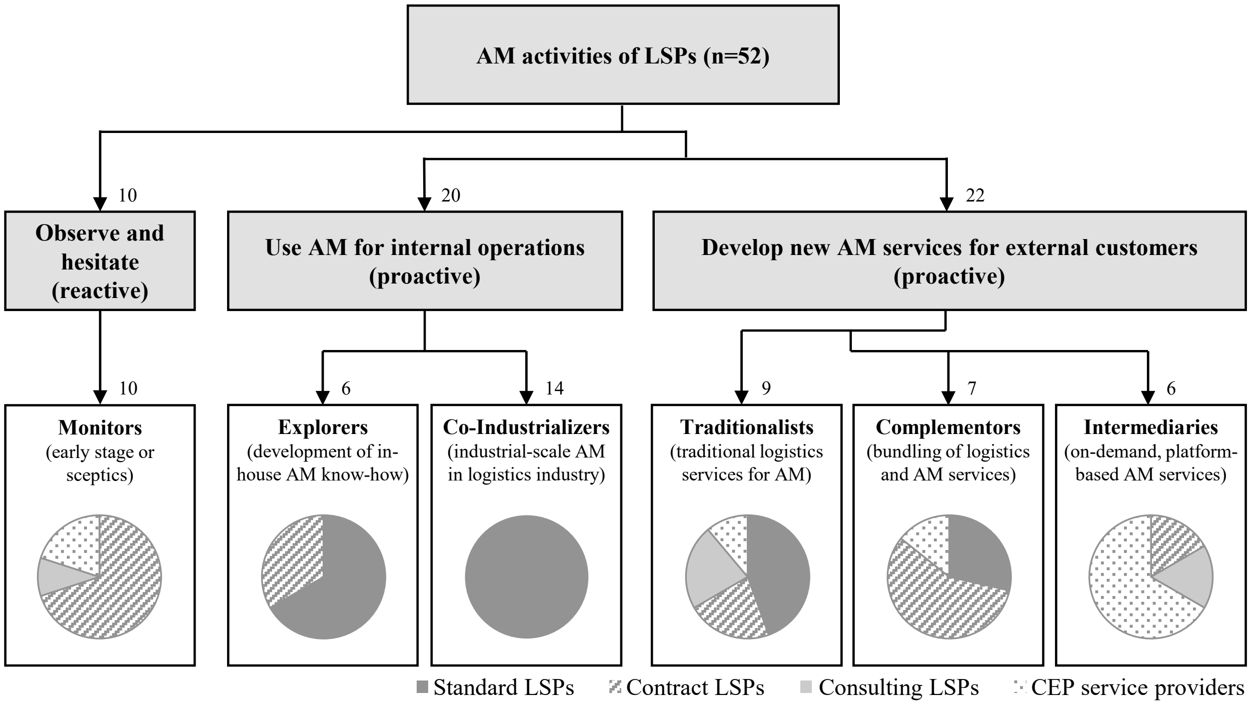



Figure 4-4: Six-cluster solution for AM activities of LSPs.

## 4.4.1 Monitors – observe and hesitate

**Monitors** predominantly subsume contract LSPs (70%) and their AM activities (see Figure 4-4). These LSPs are currently at a pre-access stage of either observing and monitoring AM as a trend or synthesizing and generating AM business concepts. Their initial AM activities do not create any business model changes at this stage and do not establish linkages to their traditional business models and customers. Based on this positioning, Monitors currently do not offer services in AM. Their aspired value proposition and value creation process are vague, largely undefined, and independent of partners, resulting in uncertainty over whether Monitors will develop an AM business model in the future. Typically, their current AM activities include gathering information on AM by joining AM industry networks (e.g., Paul Schockemöhle Logistics) and attending AM industry events (e.g., LGI Logistics Group International). Furthermore, Monitors define AM as part of their innovation strategy (e.g., Honold Logistik Gruppe), evaluate scenarios for an AM market entry (e.g., Deutsche Post), and assess the quality and applicability of AM test parts (e.g., Dachser). Their AM activities are motivated by their perceived need to prepare for the consequences of AM for their traditional business and to anticipate the future development of AM. For instance, one of the Monitors, a contract LSP, shared in our interviews, “I think the story is much more about being adaptive, […] understand the technologies, […] and know what is the right moment to step in.”

Interestingly, five Monitors (50%) continue to be at the stage of waiting since their early first contact with AM between 2013 and 2017. These firms appear uninvolved, disillusioned with the technologies’ potentials, and reluctant as they neither experience AM revolutionizing their traditional business nor perceive that AM is mature enough to meet their customers’ quality requirements presently. These Monitors point out unresolved problems in the nascent market, including intellectual property rights, product liability, quality control, and certification. For instance, one interviewee from a contract LSP raised the question, “Who will guarantee the quality of the output of the 3D printer? That is still a technical problem. […] the technologies are promising, but especially the warranty issue will take at least 15 years before we can solve it.” Public communication from the contract LSP Dachser mirrored this view: “There is still a lot of homework to do […]. Above all, there are still too few viable business models [for AM]. This is where the industry is called upon to take the initiative" (Weber, 2015). Thus, these Monitors point out that their industrial customers are responsible for pushing AM toward maturity and paving the way for new business models. As long as their customers do not take the lead and demand them to become active in AM, these Monitors do not believe in viable AM business cases and temper their expectations. The remaining Monitors (50%) began their AM activities slightly later, between 2016 and 2018, and envision their function in AM as innovators who are currently keeping track of AM to avoid missing the right time to adjust to the emerging technologies.

### 4.4.2 Explorers and Co-Industrializers – using additive manufacturing for internal operations

Explorers and Co-Industrializers are proactive users of AM for their internal operations (see Figure 4-4). Typically, they aim at using AM to serve internal demand for their maintenance, repair, and operations (MRO) activities. While Explorers build internal acceptance and know-how for AM with in-house polymer 3D printers, Co-Industrializers drive industrial AM toward maturity for the logistics sector. Almost exclusively, standard LSPs are clustered as Explorers and Co-Industrializers.

**Explorers** develop specific know-how for AM by investing in in-house polymer 3D printers. Based on this make-strategy, Explorers fulfill the function of manufacturers for their internal purposes. Their AM activities are driven by their motive of fostering organizational learning for building awareness and acceptance. Currently, their AM activities are focused on the design and manufacturing of applications with low requirements like prototypes and tools. For instance, the French railway operator SNCF runs five Fablabs with 3D printers allowing employees to experiment, test, and realize their ideas. KLM uses polymer 3D printers in eight innovation hubs to benefit from the increased flexibility of manufacturing tools and prototypes in-house. Furthermore, Explorers commonly develop in-house education programs for AM (e.g., BLG Logistics Group, HHLA) and playfully trigger employees' creativity with AM idea contests (e.g., Deutsche Bahn). Our interviews with standard LSPs reflected this view, for instance, by sharing, "We raise awareness of the technologies among our trainees in our education programs. They learn that AM will be relevant for maintenance and get the chance to know it and play around with it."

By providing their employees with easy access to AM, Explorers do not intend to offer manufacturing services for external customers in the long run or to establish professional in-house manufacturing capacities. For example, one interviewee from a standard LSP pointed out, "We are not a manufacturing firm. Therefore, I do not think that we will use AM for our maintenance professionally, but contract AM service bureaus […]." Hence, Explorers' internal AM activities do not lead to fundamental business model changes. Instead, Explorers build the necessary know-how for the novel digital technologies enabling them to sense further opportunities in AM. With the obtained AM know-how, the Explorers' profile forms a suitable basis for additional AM activities. In detail, we observe that three of the five LSPs with two disjunct sets of AM activities are clustered as Explorers, and their other business activity appears as a Co-Industrializer (Deutsche Bahn) or a Complementor (HHLA, DSV/Panalpina).

**Co-Industrializers** push AM toward industrial-scale manufacturing of spare parts for the logistics sector. Their AM activities aim to identify AM applications, test and develop materials for AM, and achieve advances and standardization of certification processes for safety-relevant AM spare parts. As such, Co-Industrializers' AM activities entail revising their traditional procurement processes of spare parts. This is a fundamental business model change of parallelizing traditional spare parts supply chains by establishing new AM spare parts supply chains. Such a dual sourcing approach can be economically beneficial. Knofius et al. (2021) calculate savings of more than 30% for sourcing AM and traditional spare parts compared to single sourcing options. In addition, it decreases the dependence of Co-Industrializers on traditional suppliers for their MRO activities. We found this to be advantageous for the asset-based business models of standard LSPs that entirely form the group of Co-Industrializers. For instance, Angel Trains, a British lessor of rolling material, publicly highlights the challenges train operators face: "[…] traditional manufacturing methods only make it cost-effective to produce high volumes of spare parts, even though an operator may only need a few obsolete train parts replaced. Lead times can also take months, exacerbating the issue even further" (Stratasys, 2020). Considering these problems, improving their spare part operations is the main motive for Co-Industrializers' AM activities. AM allows them to digitalize their inventory and reduce lead times with on-demand manufacturing (Khajavi et al., 2014). Furthermore, Co-Industrializers avoid minimum order quantities and resolve obsolescence problems, as also recognized in the OSCM literature (Chekurov et al., 2018) and in our interview with a standard LSP: "If I need the part once in two or three years, I do not want to order 500 parts and stock 499 that will probably cover my demand for the next 300 years." Alongside these benefits, Co-Industrializers are under pressure to prepare for handling the MRO activities of new generations of trains and even more so of aircraft, including a growing number of new parts designed for AM. For example, the Airbus A350 XWB already contains more than 1,000 additively manufactured new parts (Krassenstein, 2015).

To prepare for AM-based MRO and leverage the technologies' potentials, alliances are crucial for Co-Industrializers. One standard LSP in our interviews highlighted in this regard, "If everyone cooks their own soup, I do not think that we will achieve a breakthrough in the development of testing procedures and certification processes for AM. Because currently, there are still too many unanswered questions." For this reason, Co-Industrializers commonly access AM via strategic cooperation. Their partners hold various functions, the most outstanding being R&D partners, while the standard LSPs typically use their existing MRO facilities and expertise to identify AM use cases. Such combinations result in a wealth of alliances with firms from the AM domain, from traditional industries, and with academic partners. For instance, the A. P. Moller-Maersk Group piloted polymer 3D printing onboard vessels in early 2014 and found a research consortium for investigating platform-based, secure data transfer to the remote 3D printers in 2018. The German air carrier Deutsche Lufthansa bundles AM expertise with industry and research partners in an AM hub. Similarly, Deutsche Bahn founded the international AM industry network "Mobility goes Additive" in 2016, with more than 140 members recorded in 2022. The establishment of such alliances is strongly driven by the motive of learning from and with partners at the technologies' emerging stage. In this vein, Deutsche Bahn publicly shares the benefit of scaling up AM much faster based on the accelerated transfer of know-how in networks: "This is an area where we want to learn together, avoid hurdles and overcome them. And we are definitely convinced that we can do this much faster when we do it together" (Global Railway Review, 2019).

Co-Industrializers commonly complement their cooperation efforts with a make-strategy (e.g., Deutsche Lufthansa, ÖBB, A. P. Moller-Maersk Group, Port of Rotterdam) or a buy-strategy of sourcing AM parts from selected and qualified AM service bureaus (e.g., Deutsche Bahn, Trenitalia, SJ, Nederlandse Spoorwegen, Eurostar International). Our interviews indicated that buy-strategies are driven by the advantage of technological flexibility as outlined by a standard LSP: "The range of applications is so broad, and the AM processes are so diverse. Thus, we have framework agreements with AM service bureaus to secure slots and availabilities of AM machines for us."

Furthermore, Co-Industrializers demonstrate different entry times into AM. Early entrants (2015/2016) extensively digitalize their spare parts today (e.g., Deutsche Bahn has digitalized more than 300 applications for the production of more than 25.000 AM parts (Deutsche Bahn, 2021a)) and have built expertise to deal with large and demanding metal AM applications (e.g., Deutsche Lufthansa, Port of Rotterdam). Meanwhile, eight Co-Industrializers started their AM activities in a later second-wave in 2018/2019 and are currently at a stage of concretization and implementation. Typically, their first applications include non-critical "comfort" spare parts such as door handles, levers, coat hooks, fold-down tables, and armrests used for the interior of railways and aircraft.

### 4.4.3 Traditionalists, Complementors, and Intermediaries – additive manufacturing services for external customers

Traditionalists, Complementors, and Intermediaries proactively and explicitly address external customers with new AM services (see Figure 4-4). All three profiles make fundamental changes in their existing business models. While Traditionalists extend their traditional services for AM, the other two profiles create novel service bundles.

In essence, **Traditionalists** transfer their well-known mechanisms for value creation to the new AM context. Hence, their AM services are directly tied to their existing services, locations, and infrastructure and do not require them to get involved with AM technologies directly. Such extensions of services are observable for all four types of LSPs, indicating that this is an overarching pattern. Currently, Traditionalists' AM activities are mostly at the implementation stage; thus, not all LSPs routinely offer their services for AM yet. In line with this, Traditionalists' AM activities are typically triggered by their industrial customers' demand and, thus, qualify as a direct response to the need for logistics services in AM. For instance, contract LSPs offer warehousing of filaments (e.g., Hellmann Worldwide Logistics) and transportation of metal powder for AM (e.g., GROUP7 International Logistics). Consulting LSPs lower their industrial customers' entry barriers into AM with specific AM consultancy (e.g., 4flow) and develop diagnostic tools assisting in identifying suitable applications for AM (e.g., Accenture). Furthermore, our sample contains a CEP service provider that temporarily used its established online store to sell AM equipment and customizable, 3D-printed presents. This move allowed the LSP to pick up the 3D printing trend in innovative offers and exploit the increased attractiveness of selling customized niche products, as emphasized by Rayna and Striukova (2016b).

Generally, we found that LSPs gain insights into the novel AM market with the outlined traditional logistics services, and further AM business opportunities may arise from there. In this vein, one contract LSP shared in our interviews the firm's motive for transporting AM equipment (AM machines, powder, spare parts) for an AM machine manufacturer: "I think this is an opportunity to learn live about the AM market […]. And maybe our customer will help us to acquire new customers and to get started with AM-specific services."

While the aforementioned AM activities typically do not rely on partners, the integration of existing partners is central for the standard LSPs, focusing on port operators among Traditionalists. Port operators promote the attractiveness of their locations as strategic clusters for AM. With their extensive logistics infrastructure and traditional ability to connect transportation modes and information flows, they see themselves as being in an ideal position to build AM hubs. This viewpoint was also expressed in our interviews when a port operator proposed the benefits of establishing AM at ports: "You try to have as few breaks in the supply chain as possible. But you always have a natural break at the port, from water to land. You can use this break to establish AM and avoid additional breaks, for example, for a manufacturing plant 100 km further inland." In their envisioned role as integrators, port operators can bring together the pre-settled industry to jointly establish AM. The integration of emerging technologies like AM at ports promises growth, new jobs, non-core revenue streams and fosters the ports' recognition for their innovativeness. For instance, the RAMLAB at the Port of Rotterdam is currently established with 20 European partners, specializing in AM for large metal parts for the maritime industry. The port publicly articulated the vision: "Our aim is to make the Port of Rotterdam not just an important gateway for Europe, but also a leader in the development of new manufacturing methods" (Louppova, 2017). Beyond the scope of our sample, similar AM activities exist for airports (e.g., the Neighborhood 91 is currently established at Pittsburgh International Airport as an ecosystem that connects all entities of an AM supply chain (Neighborhood 91, 2022)).

**Complementors** create novel service bundles by combining AM and related logistics services into one-stop services. These so-called “logistics manufacturing services” (Hedenstierna et al., 2019, p. 761) provide (industrial) customers with additively manufactured parts as well as upfront and subsequent logistics services, including warehousing and last-mile delivery. Complementors’ AM activities are a response to customer needs and result from the fear of consequences of AM for their traditional business. Their creation of combined services is strongly linked to their existing assets, infrastructure, and traditional services. As Complementors are mostly contract LSPs (57%), they are known for their ability to highly customize services to the needs of their customers (Prockl et al., 2012). AM falls into this scheme and is coined as a value-added service for these LSPs.

In contrast to light assembly tasks conducted by LSPs in-house in traditional manufacturing, Complementors commonly rely on experts from the AM domain, partners from traditional industries, and academia for the AM process. LSPs have pronounced multiple times in our interviews that they lack specific know-how, at least for the industrial AM process. For example, one standard LSP underlined, “We are all no AM specialists.” Based on LSPs’ knowledge gaps, strategic alliances (e.g., Arvato SCM Solutions, DSV/Panalpina, DPDgroup) and joint ventures (e.g., Andreas Schmid Logistik) are frequently established to access AM. Besides, Complementors contain two standard LSPs from the maritime industry that acquired majority (HHLA) or minority (Wilh. Wilhelmsen) shares of AM service bureaus. They use the internalized know-how to accelerate access to the AM industry. One standard LSP reflected this reasoning in our interviews: “We are no technicians, and we have seen that it is not easy to build the AM know-how completely on your own. One possibility is always to ‘buy’ it, and this was the path we chose.”

In summary, similar to Traditionalists, Complementors provide logistics services in AM. However, what sets them apart from Traditionalists are their efforts of integrating AM into all-in-one logistics solutions by a single provider. Offering seamless end-to-end solutions constitutes the unique selling point of Complementors in AM. For instance, Andreas Schmid Logistik, a contract LSP, uses the slogan “3D meets logistics” to emphasize the advantage of all-inclusive service bundles (Voxeljet, 2017). Such a strong interweaving with partners in the value creation process fosters combinations of various competencies like expertise in AM, SCM, project management, product life-cycle management, and customer know-how (e.g., Visagio, Wilh. Wilhelmsen). Complementors highlight the mutual benefits of their co-created service bundles allowing the LSPs to integrate AM in their contract logistics services and fostering geographic expansion and access to the LSPs’ customers for their partners.

**Intermediaries** create AM services that are digitalized and platform-based. Their services include offering access to AM design platforms and online design advisories (e.g., La Poste, Royal Mail Group), real-time AM price calculations (e.g., Schenker), automated assignment of orders to AM service bureaus (e.g., Visagio), and advanced tracking options (e.g., PostNord). With such digital dominance, Intermediaries typically do not depend on their existing locations and infrastructure. This sets them apart from Traditionalists and Complementors. However, a “physical” add-on to their digital services is the piloting of service points for AM design or re-engineering consultancy in postal offices (e.g., TNT, Royal Mail Group, La Poste).

Intermediaries mostly include CEP service providers (67%). Taking part in the digital transformation and gradually adapting to their customers’ needs in AM are the main rationales driving these LSPs. Postal services like La Poste have experienced dynamic changes in their business, with the digitalization of letter deliveries through emails and heavy competition in the parcel business requiring them to try “entire new approaches” like AM (Stevenson, 2018). As AM service providers, Intermediaries fulfill a neutral, unbiased function of connecting their customers to actors from the AM domain. This positioning allows them to stand out against AM-specific actors, like AM machine manufacturers, that supposedly tend to talk customers into specific technologies (Gowans, 2021). The neutrality of LSPs is not specific to AM but is also valued by their customers for traditional logistics services (Hertz & Alfredsson, 2003). True to the profile's name, Intermediaries offer their customers the unique advantage of easy, fast, flexible, and low-risk access to (industrial) AM via platform solutions, acting as the intermediary between customers and AM providers. Ideally, AM requires only the "push of a button" just like online shopping for ordering digitalized parts in an intuitive, moderated, "foolproof" process and without the required investment in cost-prohibitive 3D printers/AM machines (Gowans, 2021). As evident in one of our interviews, storing the digital designs of customers for on-demand orders complements this business model: "AM enables the digitization of certain parts and the topic 'digital warehouse' will be an essential building block of AM services."

Without exception, Intermediaries cooperate with firms from the AM domain in their value creation process. Their partners' role is to provide software and platform solutions for AM and carry out the manufacturing process. Just as we observed for Complementors, these partners emphasize the mutual benefit of the cooperation as it provides them with direct access to the customer bases of Intermediaries as potential new customers. The LSPs, on the contrary, become the single point of contact for the digital service and leverage their traditional customer know-how in AM. To be more specific, LSPs' proximity to their customers' operations and direct insights into customer data and processes, such as order policies, inventory levels, and high- and low-runners (Busse & Wallenburg, 2011; Carbone & Stone, 2005), allow them to support their customers in the transition from traditional manufacturing to digital AM. As an interviewee from a contract LSP pointed out when referring to the LSP's customer know-how, "I believe that our advantage is not only geographical proximity but also informational proximity to the customer." Similarly, Schenker publicly puts it for AM as, "The logistician is demanded as a service provider and consultant, without the primary focus being on transportation chains" (Pietsch, 2020).

Table 4-3 presents the characteristic AM activities of the six profiles and their target groups to consolidate our findings for RQ1.

Table 4-3: Overview of the responses of LSPs to AM.

| Profile | *RQ1: How do LSPs respond to AM, that is, which specific AM activities of LSPs can we observe as a reaction to AM?* | | |
|---|---|---|---|
| | **Response to AM** | **Representative AM activities** | **Target group** |
| Monitors | Observe AM and **stay informed** | ▪ Joining of AM industry networks<br>▪ Attendance of AM industry events<br>▪ Integration of AM into the firm's innovation strategy<br>▪ Evaluation of concepts for an AM market entry<br>▪ Assessment of AM test parts | Internal departments (e.g., innovation management, business development) |
| Explorers | Develop **in-house know-how** for polymer 3D printing | ▪ Investment in in-house polymer 3D printers<br>▪ Manufacturing of prototypes, tools, fixtures, etc.<br>▪ AM education programs and idea contests<br>▪ Experiments and tests, permission to use polymer 3D printers for private purposes | Internal departments (e.g., education and training) |
| Co-Industrializers | Push AM toward **industrial-scale manufacturing** | ▪ Founding of alliances (actors from the AM domain, traditional manufacturing, and academic partners)<br>▪ Identification of applications for AM (spare parts)<br>▪ Testing and development of materials for AM<br>▪ Contribution to the development of industry guidelines (e.g., quality testing, certification of materials and safety-relevant spare parts for AM) | Internal departments (e.g., for MRO activities) |

*Table 4-3 continued.*

| | | | |
|---|---|---|---|
| Tradition-alists | Provide **traditional logistics services for AM** | ▪ Offering of warehousing and transportation services for AM (e.g., for filaments and metal powder)<br>▪ AM consulting services<br>▪ Selling of AM equipment in existing online stores<br>▪ Orchestration of AM clusters (e.g., at ports/airports) | Existing customers and new customers from the AM domain |
| Comple-mentors | Provide **service bundles** of **logistics services coupled with AM** as **value-added services** | ▪ Offering of integrated logistics and manufacturing service (all-in-one logistics and AM solutions, seamless/end-to-end services from a single source)<br>▪ Acquisitions and establishment of alliances and joint ventures with actors from the AM domain | Existing customers |
| Intermediaries | Provide easy access to AM with **on-demand, platform-based AM services** | ▪ Offering of platform-based AM services (e.g., design platforms, design advisory, real-time price calculation, order processing, tracking, storing of digital designs)<br>▪ Online shopping for AM (intuitive, moderated process)<br>▪ "Physical" AM service points in postal offices<br>▪ Established cooperation with AM software and platform providers and AM service bureaus | Existing customers |

## 4.5 Discussion

As our primary contribution, this study provides a comprehensive and structured picture of real-world examples of how LSPs respond to AM to enrich the young stream of business model research in the OSCM literature with an in-depth perspective on LSPs. We identify six profiles of distinct AM activities of LSPs. They further enable us to contribute to building theory in two ways: In Section 4.5.1, we derive context-specific knowledge on why the service-based logistics industry reacts to AM. This addresses RQ2. Referring to RQ3, we develop in Section 4.5.2 an AM-specific understanding of emerging technologies and business model dynamics. Finally, our research propositions may serve as a basis for subsequent confirmatory research.

### 4.5.1 Reasoning of logistics service providers for additive manufacturing

AM technologies are inherently digital and coined as enablers of digital supply chains. Hence, the reasoning of LSPs for their AM activities enables us to gain more general insights into how LSPs navigate in the digital age and try to enhance their competitiveness. With that, we tackle RQ2 and build an understanding of how the digital era impacts LSPs' traditional way of doing business. Table 4-4 summarizes the six profiles of LSPs to disentangle their reasoning and derive their resulting AM strategy based on our collected data. The following discusses overarching patterns of their reasoning, summarized in three propositions.

Our findings indicate that the different types of LSPs with their specific service scopes demonstrate distinct reasoning for their AM activities (see Table 4-4). Most standard LSPs focus on utilizing AM for their internal operations to improve their spare parts availability. Their internal orientation and focus on efficiency gains (e.g., lead times and cost reductions) are characteristic of such LSPs (Mathauer & Hofmann, 2019). Other LSPs traditionally emphasize value-added services, most notably contract LSPs (Evangelista et al., 2013; Mathauer & Hofmann, 2019), which holds true for AM as well. These LSPs understand AM as one among several opportunities outside their traditional business models for diversifying their value-added services. In terms of firm size, our findings indicate that the few SMEs with AM activities in our sample mostly make use of the "option of waiting" (Folta, 1998, p. 1011) (Monitors) or turn into providers of traditional logistics services for AM (Traditionalists). Both are risk-averse AM strategies that require limited investments and are in line with previous research suggesting a reluctance to change and a lack of human and financial resources in SME LSPs (e.g., Evangelista et al., 2013; Evangelista & Sweeney, 2006).

**Prop. 1:** *Specific types of LSPs demonstrate specific responses to AM that are consistent with their traditional behavioral patterns. We propose that the orientation of LSPs (i.e., their focus on internal improvements or diversification of value-added services) and their firm sizes (i.e., their risk aversion and ability to make large investments) are reflected by their choice of AM activities.*

LSPs have the general reputation of being not very innovative, which is reflected in their reactive firm culture and reliance on their customers to drive innovation (Busse & Wallenburg, 2011; Wagner, 2008). We show that Monitors follow this pattern by holding the industry responsible for developing an unambiguous AM market and setting impulses ("customer push") for AM activities of LSPs. However, we also propose five proactive profiles of AM activities of LSPs (see Table 4-4). Co-Industrializers actively strive to implement AM and advance the technologies to an industrial scale. LSPs are said to "adopt [a] new technology rather than generate it" (Busse & Wallenburg, 2011, p. 202). Co-Industrializers counter this literature-based view by aiming at overcoming the hurdles of the nascent market to make use of AM as a technological innovation for their MRO activities. In addition, we demonstrate how AM becomes a source for service innovations. By proposing seamless, all-in-one AM and logistics services (Complementors) and easy access to AM via platform solutions (Intermediaries), LSPs actively search for novel advantages they can offer their customers in AM. This can be interpreted as a sign of high adaptability and striving for service innovations to anticipate their customers' future needs and succeed in today's fast-moving environment (Chapman et al., 2003; Flint et al., 2005).

**Prop. 2:** *Multiple LSPs overcome their passive, reserved attitude toward innovation ("waiting for the customer push") when it comes to developing AM-based service innovations and transforming their spare parts business. We propose that their specific behavior stems from the observation that LSPs proactively adapt and prepare for their customers' needs in AM.*

Our findings further demonstrate that LSPs recognize AM as one of the recent advancements in digital technologies forcing them to react, in line with Hofmann and Osterwalder (2017). According to Cichosz et al. (2020), there is pressure on the logistics industry to move from the "analog" to the digital world. In our findings, this pressure is reflected in LSPs' perceived need to prepare for losses in their traditional business and desire to seize AM for taking part in the digital transformation. This is most pronounced in the reasoning identified for Complementors and Intermediaries, thus, mostly for contract LSPs and CEP service providers. By reacting quickly and positioning themselves in AM before the market stabilizes, they aim at generating first-mover advantages (see Table 4-4). One LSP of the Complementors suitably called this a "better shape than follow" strategy to emphasize that meaningful, solid, and prompt AM activities are necessary if LSPs truly believe in the disruption of AM for their business (Wilh. Wilhelmsen, 2019). Currently, Complementors and Intermediaries benefit from the low entry barriers in the nascent AM market (see Rayna & Striukova, 2016b). However, their fast reactions to AM also come with a trial-and-error service development (Rong et al., 2018) measurable by a high failure rate of their AM activities. For instance, we recorded that four of the 13 LSPs clustered as Intermediaries or Complementors downsized or discontinued their AM services between 2013 and 2020.

**Prop. 3.1:** *LSPs, mostly contract LSPs and CEP service providers, rush to respond to AM with trial-and-error service development and with the prospect of first-mover advantages in the nascent AM market. We propose that AM poses a fundamental threat to these LSPs' core business, including warehousing and transportation, and their reactions aim to counter the expected losses.*

Finally, we find that learning is a central reason driving LSPs in their AM activities, in particular the users of the technologies. Explorers demonstrate how LSPs apply a bottom-up approach of building user acceptance, a culture for AM, and technological understanding for the novel digital manufacturing process with in-house polymer 3D printers. Such a development of user participation is crucial for the success of integrating external technologies within firms (Stock & Tatikonda, 2008). Moreover, extensive collaborations are recognized as a success factor of digital transformation (Vogelsang et al., 2018). In this vein, Co-Industrializers extend the thought of learning by bundling AM competencies in cross-industry alliances. As an alternative approach, Traditionalists learn "live" in the AM market by offering their traditional logistics services for AM.

**Prop. 3.2:** *Learning in-house and through alliances to bridge knowledge and skill gaps is an essential element of LSPs' responses to AM. For standard LSPs as the dominant users of the technologies, learning enables building an internal knowledge base and preparing for AM-based maintenance. In addition, LSPs make use of the opportunity to learn directly on the AM market by offering logistics services for AM.*

Table 4-4: Reasoning of LSPs for AM.

| Profile | Type of LSPs | *RQ2: What are the underlying reasons for LSPs to pursue these specific AM activities?* | |
|---|---|---|---|
| | | **Identified reasons for AM activities** | **Derived AM strategy** |
| Monitors | Mostly contract LSPs (SMEs and large) | Prepare for the **consequences of AM** and try **not to miss the chance** to enter the AM market; **industry must resolve uncertainty** and **push LSPs** to offer services in AM | **"Option of waiting"** for the right timing for more involvement |
| Explorers | Mostly standard LSPs (large) | Build **awareness**, **acceptance**, and **know-how** for AM; **no intention to professionalize in-house AM** and offer manufacturing services | **Knowledge base** for sensing further business opportunities in AM |
| Co-Industrializers | Only standard LSPs (large) | **Learning from and with partners** to improve **spare parts services** in the logistics industry and **prepare** for the **MRO activities** of **new parts designed for AM** | **Active change** of the spare parts business in the **logistics industry** |
| Traditionalists | All four types of LSPs (SMEs and large) | Respond to concrete **customer demand** for logistics services in AM with the prospect of **generating additional, non-core revenue streams** | **Limited novelty** and **low risk;** opportunity to **learn** and **gain AM market insights** |
| Complementors | Mostly contract LSPs (large) | Adapt to **customer demand** and **fear of negative consequences of AM** for traditional business | **"Better shape than follow"** by **trial-and-error development** of new AM services |
| Intermediaries | Mostly CEP service providers (SMEs and large) | **Need to try new approaches and continuously adapt** to customer demand; seize opportunities in AM to take part in the **digital transformation** | **"Better shape than follow"** by **trial-and-error development** of new AM services |

### 4.5.2 Interactions between additive manufacturing activities and traditional business models

By taking a process-based perspective and focusing on business model dynamics, this study distills how AM impacts firms' traditional business models as a set of emerging, potentially disruptive technologies. More specifically, the six profiles of AM activities enhance our understanding of how LSPs' business model changes (x-axis) are linked to their existing business models (y-axis). Figure 4-5 structures these interactions for each profile and thereby addresses RQ3. Here, a high interaction implies that the LSP heavily relies on its traditional business model for its AM activities, such as existing logistics assets and infrastructure, traditional services, and pre-existing partners. We derive three propositions for the interactions that contribute to business model dynamics (e.g., Baden-Fuller & Haefliger, 2013; Chesbrough, 2007; Rong et al., 2018) with real-world insights collected from the AM context.

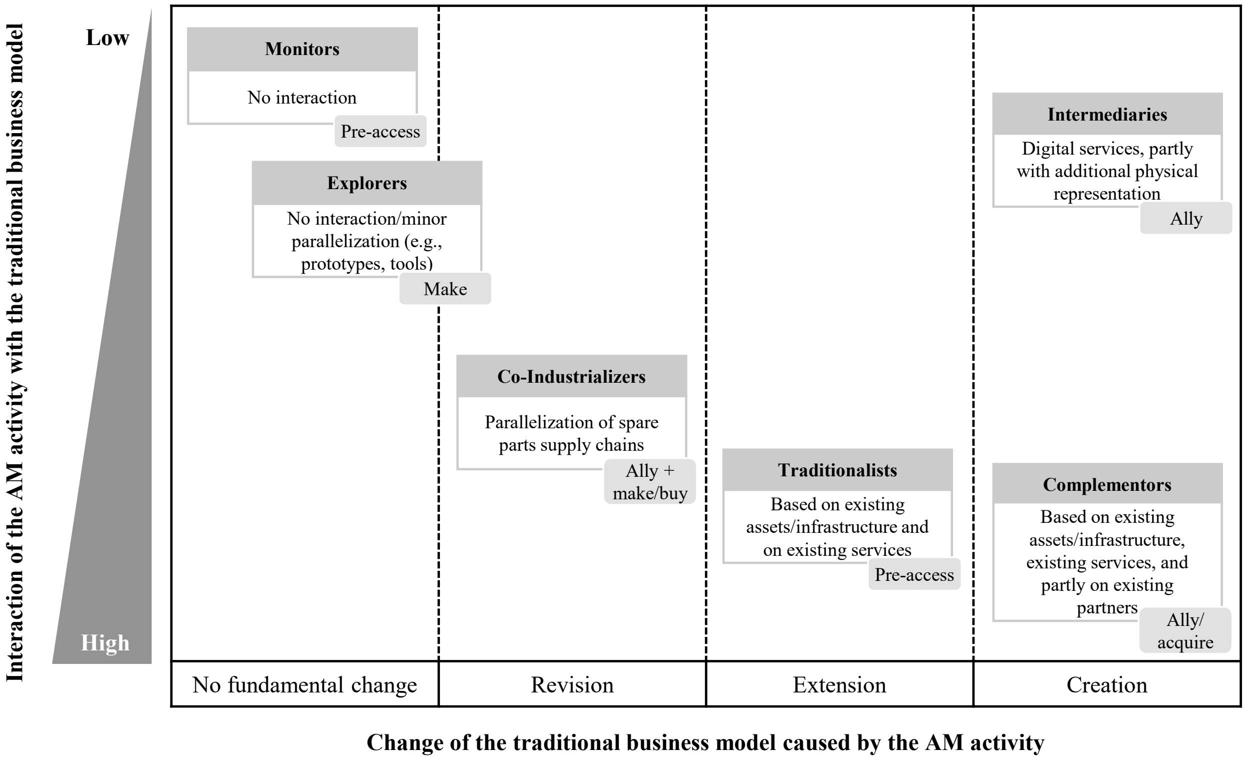



Figure 4-5: Business model changes and interactions of LSPs.

Figure 4-5 demonstrates that two profiles, Monitors and Explorers, cause no or only slight business model changes. They involve limited interaction with the LSPs' traditional business models. As continuous activities without significant resource input (e.g., experiments of employees with polymer 3D printers) or project-based activities (e.g., AM idea contests and attendance at AM industry events), they do not affect the core processes and, thus, neither the traditional business models of LSPs as also suggested by Cavalcante (2013). Moreover, the resources associated with the AM activities, including developed AM-specific knowledge and acquired assets like polymer 3D printers, do not constitute a superior resource position for these LSPs, according to the RBV (Barney, 1995). Instead, the resources allocated in the AM activities are a means of staying abreast (Monitors) and creating a knowledge base (Explorers). With that, the AM activities are intended to put LSPs in a position where they excel at recognizing business opportunities in AM and the right timing to exploit these opportunities. Following the understanding of Teece (2018), the AM activities are for now focused on building organizations with strong dynamic capabilities for sensing business opportunities in AM.

**Prop. 4:** *In the case where LSPs aim to achieve the ability to sense business opportunities, their current AM activities have marginal direct interaction with their traditional business and remain limited to comparable small resource input.*

The four remaining profiles in Figure 4-5 cause fundamental business model changes, namely business model revisions, extensions, or creations. These AM activities commonly also require strong connections to the LSPs' traditional business models, as evident for Co-Industrializers, Traditionalists, and Complementors. For these profiles, the high degree of interaction of LSPs' AM activities with their traditional business models coincides with their strong dependence on their logistics assets and competencies for AM. For instance, even though Co-Industrializers substitute traditional sourcing channels and reduce dependence on their traditional suppliers, they extensively rely on their MRO facilities and expertise for AM. Similarly, Traditionalists' and Complementors' dependence on their logistics resources and competencies results from offering logistics services for AM (Traditionalists) or reframing logistics services as all-in-one service bundles including AM (Complementors). With that, these LSPs use their dynamic capabilities to strengthen their traditional resource configurations in AM. In other words, their actions follow the logic of leveraging the same resources, which constitute their superior resource positions for their traditional logistics services to create value in AM. Eisenhardt and Martin (2000, p. 1118) term such a strategy as the "RBV's path-dependent strategic logic of leverage" and emphasize that it aims at creating a long-term competitive advantage realized through a continuous resource base. As a result, Co-Industrializers, Complementors, and Traditionalists are prime examples of the creation of rather obvious permutations of existing business models (Cavalcante, 2013; Teece, 2018). However, sticking to established patterns and committing to their established business models may hinder these LSPs from implementing major business model changes for AM, as suggested by Chesbrough (2010) and Voelpel et al. (2004).

**Prop. 5:** *LSPs who aim at leveraging their existing resource base in AM have started to develop new activities for their internal operations and external customers that exploit the potential of AM. Such activities nevertheless remain connected to the traditional LSP business model.*

Standing out in Figure 4-5, Intermediaries are the only LSPs that create new AM business models with limited interaction with their traditional services. Intermediaries' digital, platform-based AM services cut connections to capabilities and assets required for their traditionally "analog" logistics services. With that, Intermediaries position themselves in AM more clearly outside their traditional industry context. Borrowing from Prahalad (2004, p. 171), their strategy can be interpreted as diverting from their "dominant logic" in value creation. In line with this, Karim and Mitchell (2000, p. 1062) refer to a "path-breaking change," which directly contrasts the "path dependence" of the three profiles described above. Thus, Intermediaries change their resource base instead of leveraging it for AM. By using their dynamic capabilities to configure a new resource base, Intermediaries aim at moving into new competitive positions in the novel AM market. Following Eisenhardt and Martin (2000), this is an advantageous strategy in high-velocity markets like AM, where the duration of competitive advantages itself is unpredictable. The resource configuration of Intermediaries emphasizes the importance of digital assets (e.g., the service platform and digitally available designs of AM parts) and requires competencies in the digital domain (e.g., IT and software skills). With this novelty in their value creation, Intermediaries are confronted with challenges of digital business models, including secure digital infrastructure, intellectual property protection, and liability issues (Appleyard, 2015). Given these challenges in unfamiliar terrain, our findings indicate that Intermediaries oftentimes rely on partners. Hence, the core AM know-how and the necessary digital resources, particularly the software and platform solutions for the digital services, currently remain with specialists from the AM domain.

**Prop. 6:** *In extensive collaboration with AM and IT partners, some LSPs have created entirely independent AM services from their traditional logistics activities, in particular platform-based services. These LSPs aim to make use of their dynamic capabilities to configure a new resource base.*

As labeled in Figure 4-5, not only Intermediaries but also Complementors and Co-Industrializers heavily rely on alliances, making them the dominating strategy (60%) for LSPs that access AM. As a result, AM activities and related business model dynamics currently occur within LSPs and across the complementary resources of partners (McGrath, 2010). Based on the overview of AM activities of LSPs and its discussion in the context of LSPs' reasoning and business model dynamics, we propose a framework of the derived propositions in Figure 4-6.

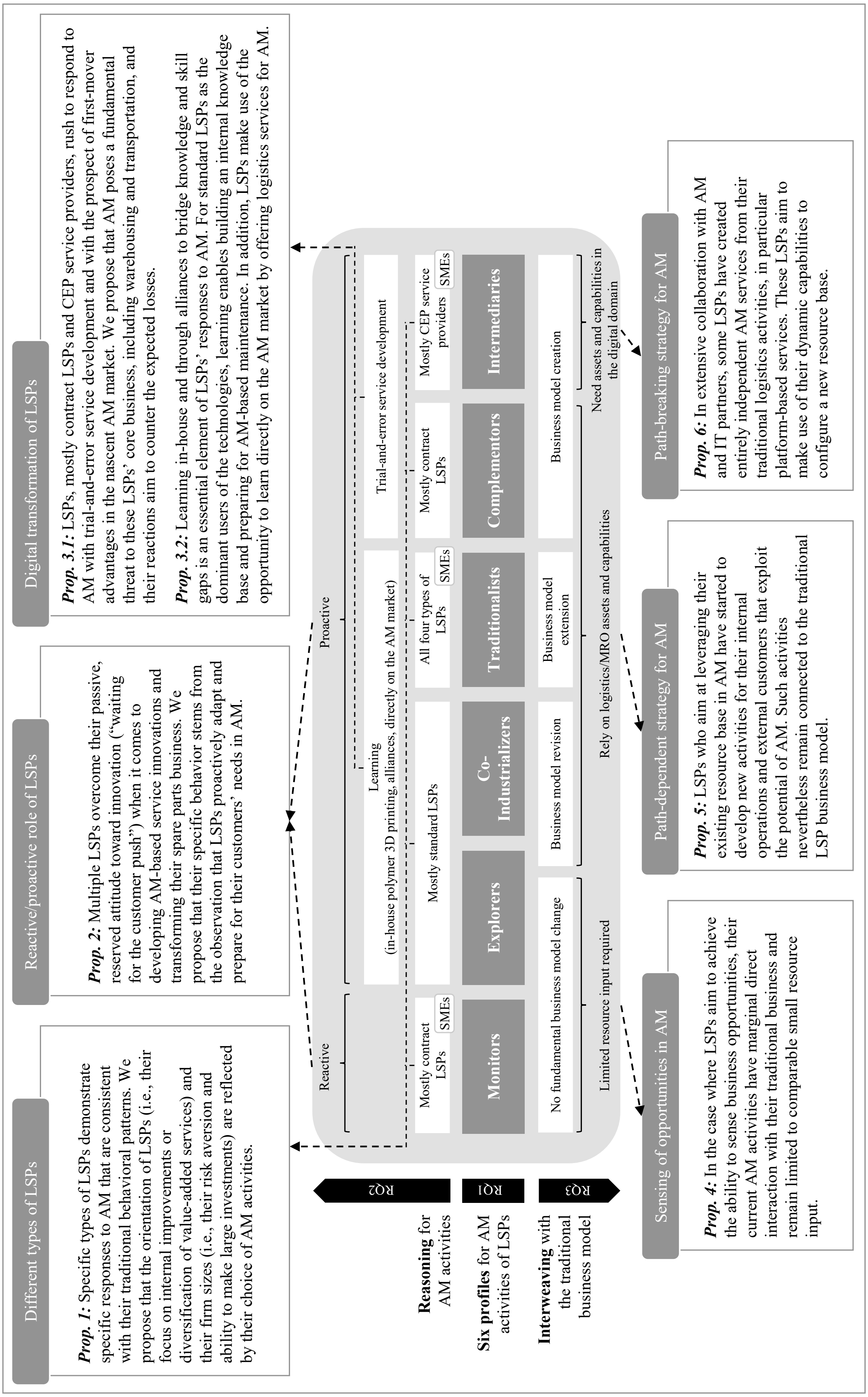



Figure 4-6: Framework of derived research propositions.

## 4.6 Concluding remarks

A growing number of LSPs have begun to tackle the threats and opportunities that come with AM. With an exploratory approach of developing a taxonomy and, on this basis, conducting a cluster analysis of the AM activities of 47 LSPs, we shed light on the responses of LSPs to AM, which remains scant to date. We present a six-cluster solution and an in-depth characterization of AM activities and resulting business model dynamics, summarized in six propositions. With that, this study extends the visions of LSPs in the young, yet static, AM business model research stream in the OSCM literature. Two derived profiles, Explorers and Co-Industrializers, indicate how LSPs approach AM as users for building internal acceptance and parallelizing their traditional spare parts supply chains. Moreover, three profiles, namely Traditionalists, Complementors, and Intermediaries, demonstrate that LSPs are in the process of establishing AM services in practice. LSPs intend to create value with specialized logistics services in AM by heavily resting on their traditional services and combinations with AM. In addition, we also find LSPs implementing digital, platform-based AM services outside their traditional comfort zone.

### 4.6.1 Managerial insights

As AM technologies are still emerging, LSPs are currently moving beyond the stage of conceptualizing and experimenting with AM activities. The taxonomy of AM activities allows practitioners to gain a nuanced view of the dimensions and characteristics of LSPs' responses to AM at this formative stage. Managers of LSPs can use the taxonomy and the additional guidance provided in the Supplementary Material A as a tool to design new AM activities or classify existing ones. Furthermore, they can compare their AM activities with the six proposed profiles since they offer holistic views on viable paths of how LSPs enter the realm of digital AM supply chains.

By analyzing the six profiles, we provide additional insights for managers of LSPs. First, we reveal that the literature-based vision of LSPs as manufacturers in AM is less pronounced in practice yet. Except for Explorers' creation of awareness with in-house polymer 3D printers, we observe only a few examples of LSPs in a manufacturing role. In particular, mastering industrial AM is perceived as challenging, and our findings indicate that standard LSPs with serious intentions to manufacture safety-relevant spare parts have a suitable manufacturing background from their traditional MRO activities. Second, we raise awareness that cooperation is currently key for LSPs' AM activities. Users of AM intensively cooperate in alliances within the logistics and AM industry for knowledge transfer. For the development of new or extended AM services that go beyond the scope of traditional logistics services, LSPs rely on experts from the AM domain for their design and manufacturing resources and software and platform solutions. Third, our results indicate that not all LSPs position themselves in the nascent AM market rapidly. Several LSPs wait for their customers to demand their AM services. Given the inherent customer orientation and desire to anticipate future demand of contract LSPs and CEP service providers, their growing engagement in AM highly depends on a stabilizing demand of industrial customers and end consumers since the hype has flattened.

### 4.6.2 Limitations and paths for future research

This study comes with the following limitations. The taxonomy provides a snapshot of current AM activities. Hence, it needs to be revised and extended to keep abreast of the positioning of LSPs in the fast-moving AM market. A further limitation of our study lies in its focus on the value creation of LSPs in AM. Investigating the mechanisms for capturing value from AM will be feasible once more LSPs have advanced in their early-stage AM activities. To gain extensive insights into their revenue mechanisms and cost structures, such a study would benefit from a different methodological approach, potentially an in-depth case study.

In addition, specific characteristics of our sample (i.e., the geographic focus and high share of large LSPs) entail that our findings foremostly speak for larger Western European LSPs. This poses a challenge because the composition of our sample may bias LSPs' approaches toward AM and interactions within the AM ecosystem. Thus, it will be valuable to classify and compare LSPs' AM activities in different geographic regions outside Western Europe. With increasing AM dissemination among industry and consumers, it will likely also become feasible to collect data from AM activities of more SMEs, thereby facilitating a refinement of the taxonomy and resulting cluster solution.

Finally, this study has not focused on investigating how LSPs combine multiple AM activities. Our results initially indicate Explorers as a suitable basis for additional AM activities, and their interplay requires further investigations.

Despite these limitations, this study provides a comprehensive understanding of the reactions and business model dynamics of LSPs. On this basis, the six profiles of AM activities encourage broader paths for future research: from the perspective of LSPs, future work could target the performance and organizational implications of the profiles. For instance, the profiles demonstrate that LSPs face significant resource gaps for AM. As AM requires different skills (e.g., more analytical design, engineering, and IT skills) and is expected to reduce manual labor (Ben-Ner & Siemsen, 2017), LSPs face new organizational challenges. Follow-up questions could touch on the workforce qualification, appropriate organizational structure, firm culture, and further social implications of embedding the profiles within LSPs. Thereby, AM could also be compared with how LSPs integrate other product and service innovations.

From an AM ecosystem perspective, the profiles emphasize the cooperation efforts of LSPs. However, the competitive pressure in the nascent AM market is high (Öberg, 2019), which raises the question of whether the current partners of LSPs may eventually turn into competitors for AM services. In this vein, future work could investigate the coordination, contractual arrangements, and cooperative and competitive dynamics between LSPs and their partners from the AM domain (e.g., AM service bureaus and AM software and platform providers).

Moreover, each profile has specific supply chain consequences. In light of the expectation of shorter, less complex, and decentralized AM supply chains (Durach et al., 2017b), future work could explore the compatibility of the profiles with such supply chain designs. For example, by additively manufacturing spare parts at the point of demand (Co-Industrializers) or by matching AM orders with local AM service bureaus via platform-based services (Intermediaries), LSPs could even foster decentralization and the reduction of traditional logistics services in supply chains. Other profiles (Traditionalists and Complementors) rely on a sustaining need for traditional logistics services in AM supply chains and, hence, significantly differ in their supply chain consequences (e.g., the geographic dispersion and environmental performance).

## Appendix A: Taxonomy development process

The taxonomy development process consisted of one conceptional iteration, three subsequent empirical iterations, and one test iteration. In the first iteration, we used the concept of business model dynamics (see Section 4.2.1), and existing classifications of AM business models as a reference point to develop initial characteristics of LSPs' AM activities and organize them in dimensions. We identified 15 existing classifications related to AM business models in the OSCM literature as detailed in Table A4-5. Eight of them were suitable to contribute to our initial taxonomy. In particular, we used the classifications for LSPs from Pause and Marek (2019), for AM machine manufacturers from Holzmann et al. (2020a), and for AM service bureaus from Rogers et al. (2016), Chaudhuri et al. (2017), Chaudhuri et al. (2019), and Holzmann et al. (2020b) as inputs for the initial taxonomy.

Table A4-5: Classifications related to AM business models identified in the OSCM literature.

| Actors | Topic of classification | Study | Approach | Data source |
|---|---|---|---|---|
| Incumbents | AM business models of manufacturing firms | Savolainen and Collan (2020a) | Typology | Literature-based |
| | | Bogers et al. (2016) | Typology | Literature-based |
| | Scenarios for LSPs in AM spare parts supply chains | Pause and Marek (2019) | Typology | Conceptual |
| | User entrepreneur business models in AM | Holzmann et al. (2017) | Typology | Literature-based |
| | | | Taxonomy | 8 user entrepreneurs from North America and Europe |
| New entrants from the AM domain | Business models of AM service bureaus | Rogers et al. (2016) | Typology | Literature-based |
| | | | Taxonomy | Assignment of 404 AM service bureaus from DACH and Benelux states to classes |
| | | Chaudhuri et al. (2017) | Taxonomy | 3 AM service bureaus and 9 manufacturing firms from Germany and Denmark |
| | | Chaudhuri et al. (2019) | Taxonomy | 3 AM service bureaus and 9 manufacturing firms from Germany and Denmark |
| | | Holzmann et al. (2020b) | Taxonomy | 141 AM service bureaus from Europe (69) and North America (72) |
| | Business models of AM machine manufacturers | Holzmann et al. (2020a) | Taxonomy | 48 AM machine manufacturers from Europe (23) and North America (25) |
| | Services of online 3D printing platforms | Rayna et al. (2015) | Typology | Literature-based |
| | | | Taxonomy | 22 online 3D printing platforms from North America (10), the UK (3), continental Europe (7), and Australasia (2) |
| | | Kwak et al. (2018) | Typology | Exemplary open-source hardware platforms, 42 online service platforms, 27 low-cost software platforms, 32 free design software platforms, exemplary crowdfunding platforms (international) |
| | Business models for AM consulting | Bugdahn et al. (2019) | Taxonomy | 9 AM firms from Germany |
| | Mode of business and involvement of AM firms | Baumann and Roller (2017) | Taxonomy | 276 AM firms from Germany |
| | Startups in the AM industry | Hahn et al. (2014) | Taxonomy | 79 AM startups (international) |
| | E-commerce channels for AM | Eyers and Potter (2015) | Typology | Literature-based and cases illustrating e-commerce channels for AM (based on interviews and secondary research) |

On this conceptual basis, we applied real-world examples of AM activities of LSPs to the taxonomy. These examples allowed us to revise, refine, and extend the dimensions and characteristics by acting as an empirical counterpart. The examples were purposively gathered from multiple sources, starting with AM activities of LSPs that we identified in the existing OSCM literature (second iteration). Additional real-world examples were known by the authors beforehand from a multiple-case study conducted prior to this study (third iteration). As we noticed that the taxonomy still lacked the perspective of standard LSPs involved in air freight operations, we used two broad AM industry news websites to identify AM activities of specifically such LSPs (fourth iteration). We chose to terminate the taxonomy development process when at least one LSP is classified under every characteristic of every dimension, and no characteristics or dimensions have been adjusted (i.e., added, removed, split, or merged) in the last iteration. This termination condition was met after 18 classified LSPs in the fourth iteration resulting in a taxonomy of 68 characteristics along 15 dimensions. Based on the AM activities of three LSPs that we identified during the empirical iterations, we used an additional fifth iteration to test the taxonomy. Information about all real-world examples used for the empirical iterations and the test iteration were obtained via web searches (search syntax: ("name of the LSP") AND ("additive manufacturing" OR "3D printing" OR "3D-Druck")). Table A4-6 details the conceptual and empirical sources for each iteration.

Table A4-6: Sources of the conceptual-to-empirical taxonomy development process.

| It. | Approach | Topic | Sources |
|---|---|---|---|
| 1 | Conceptual | Business model dynamics | Cavalcante et al. (2011); Cavalcante (2013) |
| | | Iterative business model design process | Amit and Zott (2016) |
| | | Dynamic capabilities | Teece (2018) |
| | | Technology adoption of LSPs | Carbone and Stone (2005); Mathauer and Hofmann (2019) |
| | | Existing AM business model classifications | Baumann and Roller (2017); Bugdahn et al. (2019); Chaudhuri et al. (2019); Chaudhuri et al. (2017); Holzmann et al. (2020a); Holzmann et al. (2020b); Holzmann et al. (2017); Pause and Marek (2019); Rayna et al. (2015); Rogers et al. (2016); Savolainen and Collan (2020a) |
| 2 | Empirical | 7 LSPs with AM activities identified in the OSCM literature | **Standard LSPs:** Etihad Airways (Gasman, 2019)<br>**Contract LSPs:** DSV/Panalpina (Hedenstierna et al., 2019)<br>**CEP service providers:** UPS (Arbabian, 2022; Ryan et al., 2017), Deutsche Post (Rehnberg & Ponte, 2018), FedEx (Gress & Kalafsky, 2015), La Poste (Rayna & Striukova, 2016b; Weller et al., 2015), United States Postal Service (Boon & van Wee, 2018) |
| 3 | Empirical | 6 LSPs with AM activities identified in a multiple-case study prior to this study | **Standard LSPs:** Two national rail operators, one regional rail operator, one port operator<br>**Contract LSPs:** Two international freight forwarders and warehouse operators |
| 4 | Empirical | 5 LSPs related to aviation retrieved from two AM news websites (https://3dprintingindustry.com, https://www.3druck.com) | **Contract LSPs:** Pittsburgh International Airport, Emirates, Qatar Airways, Air New Zealand, Singapore Airways |
| 5 | Test after ending conditions were met | 3 LSPs identified in iteration 2 to 4 | **Contract LSPs:** Toll Group, Yamato Transport<br>**CEP service providers:** Singapore Post |

## Appendix B: Information about the sample of 47 LSPs

Table A4-7: Sample of 47 LSPs.

| Type of LSPs | Core services | Firm name | Country of headquarters | Revenue in 2019 (millions) | Number of employees | Founding year |
|---|---|---|---|---|---|---|
| Standard LSPs (n=21) | Port services (transshipment, warehousing) | HHLA – Hamburger Hafen und Logistik | Germany | 1,383 € | 6,296 | 1885 |
| | | Duisburger Hafen | Germany | 271 € | 1,450 | 1926 |
| | | Bayernhafen | Germany | 40 € | 167* | 2005 |
| | | TMHG – Transportwerk Magdeburger Hafen | Germany | 10 € | 74* | 1992 |
| | | Port of Rotterdam | The Netherlands | 707 € | 1,200 | 1932 |
| | Shipowners and maritime services | A. P. Moller-Maersk Group | Denmark | 32,182 € | 80,000 | 1904 |
| | | Wilh. Wilhelmsen | Norway | 756 € | 15,065 | 1861 |
| | Rail (freight) transportation services | Deutsche Bahn | Germany | 44,431 € | 323,944 | 1994 |
| | | Hamburger Hochbahn | Germany | 534 € | 6,074 | 1911 |
| | | ÖBB – Österreichische Bundesbahnen | Austria | 6,950 € | 42,982 | 1923 |
| | | SBB – Schweizerische Bundesbahnen | Switzerland | 8,921 € | 32,535 | 1902 |
| | | Nederlandse Spoorwegen | The Netherlands | 6,661 € | 36,600 | 1938 |
| | | Trenitalia | Italy | 5,950 € | 24,826 | 2000 |
| | | SNCF – Société nationale des chemins de fer français | France | 33,311 € | 272,721 | 1938 |
| | | SJ | Sweden | 848 € | 4,618 | 2001 |
| | | Eurostar International | Great Britain | 1,134 € | 1,500 | 1999 |
| | Leasing of trains and fleet services | Angel Trains | Great Britain | 410 € | 135 | 1994 |
| | Air (freight) transportation services | Deutsche Lufthansa | Germany | 36,424 € | 138,353 | 1953 |
| | | Air France-KLM Group | France | 27,200 € | 83,000 | 2004 (merger) |
| | | IAG – International Airlines Group (British Airways, Iberia) | Spain | 25,506 € | 66,034 | 2011 (merger) |
| | | easyJet Airline Company | Great Britain | 7,241 € | 15,000 | 1995 |
| Contract LSPs (n=14) | Organization and execution of road freight transportation and various customized services | Andreas Schmid Logistik | Germany | 159 € | 1,304 | 1928 |
| | | Paul Schockemöhle Logistics | Germany | 115 € | 854 | 1966 |
| | | GROUP7 International Logistics | Germany | 128 € | 600 | 2006 |
| | | Arvato SCM Solutions (as a part of Bertelsmann) | Germany | 4,175 € | 77,342 | 1835 (Bertelsmann) |
| | | LGI Logistics Group International (acquired by Elanders) | Germany | 900 € | 7,200 | 1908 (Elanders) |
| | | Seifert Logistics Group | Germany | 210 € | 1,796 | 1947 |
| | | Honold Logistik Gruppe | Germany | 246 € | 1,400 | 1879 |
| | | Hellmann Worldwide Logistics | Germany | 2,419 € | 10,190 | 1871 |

*Table A4-7 continued.*

| | | | | | | |
|---|---|---|---|---|---|---|
| | | BLG Logistics Group | Germany | 1,158 € | 11,720 | 1877 |
| | | Dachser | Germany | 5,657 € | 30,995 | 1930 |
| | | Schenker | Germany | 17,091 € | 76,200 | 1872 |
| | | Kühne + Nagel International | Germany | 19,526 € | 81,900 | 1890 |
| | | Augustin Quehenberger Group | Austria | 460 € | 2,900 | 1983 |
| | | DSV (acquired Panalpina) | Denmark | 12,736 € | 61,216 | 1976 |
| Consulting LSPs (n=4) | Consulting, software, and technologies | Barkawi Management Consultants | Germany | 13 € | 69* | 1994 |
| | | 4flow | Germany | 34 € | 261 | 2000 |
| | | Visagio | Great Britain/Brazil | 24 € | 127* | 2003 |
| | | Accenture | Ireland | 36,261 € | 406,000 | 1989 |
| CEP service providers (n=8) | Transportation of small, light-weight parcels | Deutsche Post | Germany | 63,341 € | 571,974 | 1969 |
| | | Hermes Europe | Germany | 3,500 € | 15,500 | 1972 |
| | | TNT Express (acquired by FedEx) | The Netherlands | 62,033 € | 450,000 | 1971 |
| | | DPDgroup (as a part of La Poste) | France | 7,800 € | 48,000 | 1976 |
| | | PostNord | Sweden | 3,727 € | 28,627 | 2009 |
| | | Royal Mail Group | Great Britain | 12,531 € | 165,072 | 1516 |
| | | La Poste | France | 25,983 € | 249,304 | 1576/ 1991 |
| | | Post CH | Switzerland | 6,427 € | 39,670 | 1849 |

Data retrieved from Federal Ministry of Justice and for Consumer Protection (2021) and complemented with data from firm websites.
* Small and medium-sized enterprise (SME) according to EU recommendation 2003/361 (European Commission, 2003).

## Appendix C: Information about the interviews

### Semi-structured interview protocol (relevant excerpt for this study)

1. *Background information*
   a. Information about the interviewee (name, years in the firm, professional and educational background)
   b. Interviewee's relation to AM (job description, responsibilities, connection to AM)
   c. Information about the LSP (firm name, years in existence, size, number and distribution of firm locations, key logistics services)
2. *Firm's state of AM activities*
   a. Start of AM activities (first AM activities, point in time)
   b. Reasons for initiation of AM activities
   c. Timeline of AM activities (involved employees, involved partners)
   d. Current AM activities (status of the current AM activities, plans for future AM activities)
3. *Nexus of the firm's AM activities and traditional business model*
   a. Perception of AM (e.g., as a threat/opportunity for the traditional business model, as complementary/disruptive technologies)
   b. Expected or already observable effects of AM on the traditional business (e.g., on warehousing and transportation services, on value-added services)

c. Expectations for the role of the firm/LSPs in the AM market?
   - Which new or adapted services do you offer/expect to offer in AM?
   - Which competencies/assets do you need (in-house) for these AM services?
   - Which partners do you need for these AM services and what is the role of these partners?
   - What is the role of your firm in AM? Can you image your firm/LSPs in the role of a manufacturer in AM?

d. Do you/LSPs have a significant advantage/disadvantage in AM compared to other supply chain actors? What is special about LSPs?

4. *Wrap up*
   a. What are the critical milestones for future AM development?
   b. If you could change one existing condition/limitation, what would that be?

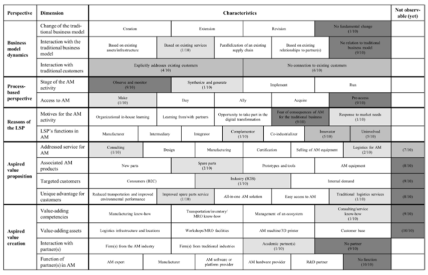
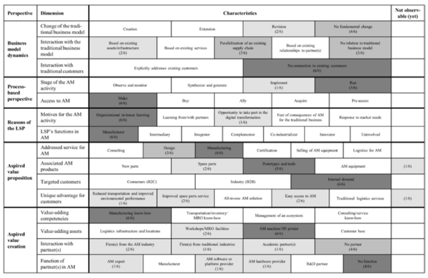
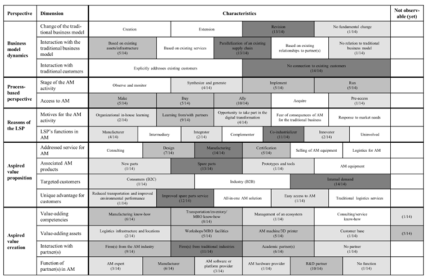
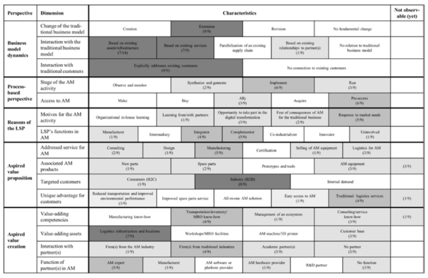
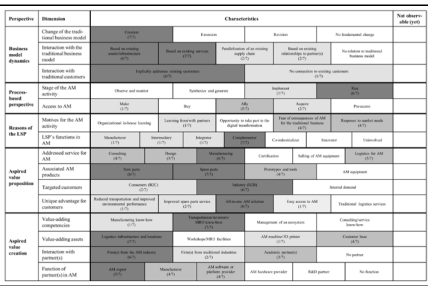
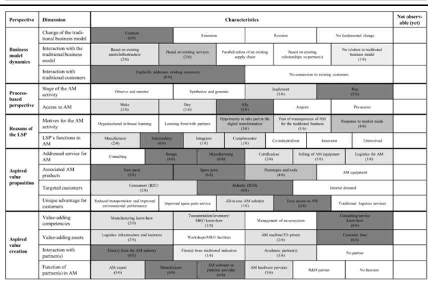
Table A4-8: Information about the eight interviews.

| Firm | Type of LSP | Traditional services | Interview type | Interview duration | No. of inter-viewers | No. of inter-viewees | Job position of interviewee |
|---|---|---|---|---|---|---|---|
| L1 | Standard LSP | Passenger rail transportation | Telephone | 0:46 | 1 | 1 | Network Logistics and Customer Manager |
| L2 | Standard LSP | Passenger rail transportation | Face-to-face | 1:01 | 1 | 1 | Head of Technical Development[a] |
| L3 | Standard LSP | Port logistics | Face-to-face | 1:01 | 1 | 2 | Head of Strategic Projects, Economist |
| L4.1 | Standard LSP | Passenger and rail freight transportation | Telephone | 0:51 | 1 | 1 | Maintenance Plant Manager |
| L4.2 | Standard LSP | Passenger and rail freight transportation | Telephone | 0:37 | 1 | 1 | Technology Scout and Material Expert |
| L5 | Contract LSP | Warehousing; sea, air, and road freight transportation | Face-to-face | 1:07 | 2 | 1 | Head of Additive Manufacturing[a] |
| L6 | Contract LSP | Warehousing; road freight transportation | Face-to-face | 0:42 | 1 | 1 | Business Development Industrial |
| L7 | Contract LSP | Warehousing; sea, air, and road freight transportation | Video | 0:44 | 2 | 1 | Head of Contract Logistics Innovation Europe |

[a] Internal data provided by the interviewee.

## Appendix D: Six-cluster solution

Table A4-9: Assignment of the AM activities of the 47 LSPs to the six clusters.

| Cluster | Included LSPs | Classification scheme (taxonomy) |
|---|---|---|
| Monitors (n=10) | **7 contract LSPs:** Paul Schockemöhle Logistics, LGI Logistics Group International, Seifert Logistics Group, Honold Logistik Gruppe, Dachser, Kühne + Nagel International, Augustin Quehenberger Group<br>**1 consulting LSP:** Barkawi Management Consultants<br>**2 CEP service providers:** Deutsche Post, Hermes Europe |  |
| Explorers (n=6) | **4 standard LSPs:** HHLA – Hamburger Hafen und Logistik, SNCF – Société nationale des chemins de fer français, Deutsche Bahn, Air France-KLM Group<br>**2 contract LSPs:** BLG Logistics Group, DSV/Panalpina |  |
| Co-Industrializers (n=14) | **14 standard LSPs:** Port of Rotterdam, A. P. Moller-Maersk Group, Nederlandse Spoorwegen, Trenitalia, Eurostar International, SJ, Deutsche Bahn, Angel Trains, Hamburger Hochbahn, SBB – Schweizerische Bundesbahnen, ÖBB – Österreichische Bundesbahnen, IAG – International Airlines Group, easyJet Airline Company, Deutsche Lufthansa |  |
| Traditionalists (n=9) | **4 standard LSPs:** Port of Rotterdam, Duisburger Hafen, Bayernhafen, TMHG – Transportwerk Magdeburger Hafen<br>**2 contract LSPs:** Hellmann Worldwide Logistics, GROUP7 International Logistics<br>**2 consulting LSPs:** 4flow, Accenture<br>**1 CEP service provider:** Post CH |  |
| Complementors (n=7) | **2 standard LSPs:** HHLA – Hamburger Hafen und Logistik, Wilh. Wilhelmsen<br>**4 contract LSPs:** Andreas Schmid Logistik, GROUP7 International Logistics, Arvato SCM Solutions, DSV/Panalpina<br>**1 CEP service provider:** DPDgroup |  |
| Intermediaries (n=6) | **1 contract LSP:** Schenker<br>**1 consulting LSP:** Visagio<br>**4 CEP service providers:** Royal Mail Group, La Poste, TNT Express, PostNord |  |

## Appendix E: Investigation of dependencies between the six clusters and the dimensions

Table A4-10: Pearson's chi-squared test of independence and Cramér's V among the clusters and dimensions.

| Variable 1 (clusters) | Variable 2 (characteristics per dimension) | Pearson's chi-squared test of independence | | | Cramér's V |
|---|---|---|---|---|---|
| | | Sample | $\chi^2$ | p-value | |
| Monitors<br>Explorers<br>Co-Industri-alizers<br>Traditionalists<br>Complementors<br>Intermediaries | **Change of the traditional business model:**<br>Creation, Extension, … | n=52 | 140.32 | $2.2*10^{-16}$ | 0.95 |
| | **Interaction with the traditional business model:**<br>Based on existing assets/infrastructure, Based on existing services, … | n=52 | 113.94 | $5.02*10^{-9}$ | 0.66 |
| | **Interaction with traditional customers:**<br>Explicitly addresses existing customers, No connection to existing customers | n=52 | 38.952 | $2.43*10^{-7}$ | 0.87 |
| | **Stage of the AM activity:**<br>Observe and monitor, Synthesize and generate, … | n=52 | 60.074 | $2.45*10^{-7}$ | 0.62 |
| | **Access to AM:**<br>Make, Buy, … | n=52 | 109.06 | $2.57*10^{-8}$ | 0.65 |
| | **Motives for the AM activity:**<br>Organizational in-house learning, Learning from/with partners, … | n=52 | 105.91 | $7.21*10^{-8}$ | 0.64 |
| | **LSP's functions in AM:**<br>Manufacturer, Intermediary, … | n=52 | 201.82 | $1.69*10^{-12}$ | 0.88 |
| | **Addressed service for AM:**<br>Consulting, Design, … | n=45 | 90.39 | $6.8*10^{-3}$ | 0.63 |
| | **Associated AM products:**<br>New parts, Spare parts, … | n=40 | 84.614 | $4.2*10^{-7}$ | 0.65 |
| | **Targeted customers:**<br>Consumers (B2C), Industry (B2B), … | n=43 | 52.312 | $1.03*10^{-4}$ | 0.55 |
| | **Unique advantage for customers:**<br>Reduced transportation and improved environmental performance, Improved spare parts service, … | n=42 | 83.84 | $6.9*10^{-6}$ | 0.63 |
| | **Value-adding competencies:**<br>Manufacturing know-how, Transportation/inventory/MRO know-how, … | n=41 | 66.075 | $1.6*10^{-4}$ | 0.57 |
| | **Value-adding assets:**<br>Logistics infrastructure and locations, Workshop/MRO facilities, … | n=37 | 70.15 | $5.63*10^{-4}$ | 0.69 |
| | **Interaction with partner(s):**<br>Firm(s) from the AM industry, Firm(s) from traditional industries, … | n=52 | 72.248 | $2.15*10^{-4}$ | 0.53 |
| | **Function of partner(s) in AM:**<br>AM expert, Manufacturer, … | n=52 | 118.13 | $1.1*10^{-3}$ | 0.67 |

Significance level of 0.05.

## Appendix F: Representative quotes

### Monitors

Table A4-11: Representative quotes for Monitors.

| Source | Representative quotes |
|---|---|
| Publicly available information | **Augustin Quehenberger Group:** “Logistics will not become less but different in the future – and you should prepare for this early on.” (Augustin Quehenberger Group, 2017)<br>**Paul Schockemöhle Logistics:** “And when it comes to future topics such as 3D printing, we try to anticipate and adapt to them. That is why we have joined the initiative ‘Mobility goes Additive’ […].” (Goodyear Dunlop Tires Germany, 2021)<br>**Hermes Europe:** “If our customers want us to [3D] print products, then we will start offering it.” (Müller, 2016)<br>**Deutsche Post:** “For service providers to become part of [AM] value chains of the industry, both sides still need to develop business models that pay off.” (Kümmerlen, 2015) |
| Interviews | **Contract LSP (L7):** “In the short term, we do not see 3D printing taking over all warehouses. Because of costs and speed, and warranty issues.”<br>**Contract LSP (L6):** “Let us explore 3D printing to see what is going on. What is the future role of the LSP? Is it already the megatrend as described everywhere? How far has the industry come?” |

### Explorers

Table A4-12: Representative quotes for Explorers.

| Source | Representative quotes |
|---|---|
| Publicly available information | **Deutsche Bahn:** “3D printing is an integral part of vocational training at DB. Trainees at our depots learn about it during their courses. This includes working independently on designing and printing materials and equipment for everyday use.” (Deutsche Bahn, 2021b)<br>**SNCF:** “SNCF Group has a total of five FabLabs – Fabrication Laboratories where our employees can invent new tools and share, test and realize ideas, using 3D printers […].” (SNCF, 2021)<br>**BLG Logistics Group:** “The aim was to integrate the complex handling of 3D printing into the education program and thus, […], to experience concrete possibilities for applications of new technologies […].” (BLG Logistics Group, 2021) |
| Interviews | **Standard LSP (L3):** “To understand the impact of AM on logistics processes, we bought polymer 3D printers and use them for experimenting and manufacturing small parts.”<br>**Standard LSP (L4.1):** “They come up with a lot of ideas. They simply try them out, learn how to control the 3D printer from the computer, translate their requirements, and ultimately transfer a 3D model to the 3D printer.”<br>**Standard LSP (L4.2):** “The trainees in the vehicle maintenance plants have desktop 3D printers to design small auxiliary parts, such as hearing protection covers, or small levers, or parts that make work easier.” |

### Co-Industrializers

Table A4-13: Representative quotes for Co-Industrializers.

| Source | Representative quotes |
|---|---|
| Publicly available information | **ÖBB:** “The aim of this cooperation is to accelerate the lengthy development cycles and to generate synergies that will enable all railway companies to use the advantages of AM more quickly as standard.” (Spiess, 2020)<br>**Deutsche Bahn:** “To achieve a breakthrough of the technologies, we have established an open, international network that covers all aspects of the value chain, particularly for spare parts.” (Vogt, 2017)<br>**SJ:** “[…] we recognize that the industry must work together in order to advance the technology and make it available to the market.” (Stjernudde, 2020) |

*Table A4-13 continued.*

| | |
|---|---|
| | **Deutsche Lufthansa:** “The collaboration will also help drive the industrialization of AM forward, as the study results will be shared with relevant industry bodies to support defining standards for the qualification and approval of aircraft components.” (Lufthansa Technik, 2018)<br>**IAG:** “Like many airlines, British Airways is first interested in leveraging 3D printing for the production of non-critical cabin parts, such as tray tables and entertainment systems.” (Boissonneault, 2019) |
| Interviews | **Standard LSP (L1):** “There are many technologies and there is no clear winner. So, it is currently not convenient to additively manufacture our own parts.”<br>**Standard LSP (L2):** “The know-how that everyone has acquired must be brought together in a coordinated way. If it always remains behind the walls of a research institute or a firm, then it will not work.”<br>**Standard LSP (L4.1):** “For interior equipment, such as hooks, controls, covers, etc. in the passenger area, there are endless opportunities [for AM] the moment a supplier simply has too long lead times or is no longer available.”<br>**Standard LSP (L4.2):** “The use of AM and its importance has developed and changed massively. If I take coat hooks, for example, as an initial application and now we talk about large, heavy, massive mobility-relevant steel parts that we manufacture.” |

## Traditionalists

Table A4-14: Representative quotes for Traditionalists.

| Source | Representative quotes |
|---|---|
| Publicly available information | **Bayernhafen:** “Trimodal inland ports are ideal locations for 3D printing […] because they are home to industrial and logistics firms that increasingly rely on 3D printing.” (Bayernhafen, 2017)<br>**Group7 International Logistics:** “And Group7 wants a share of this pie and has further developed its business models for this purpose, now including the transportation of metal powder [for AM].” (Hassa, 2018)<br>**Accenture:** “To help companies navigate this new territory, Accenture has developed a diagnostic tool to identify potential parts and products that might be eligible for 3D printing.” (Accenture, 2014) |
| Interviews | **Standard LSP (L3):** “Ports offer an advantage for AM. This is not an absurd idea but quite plausible. […] it does not matter if you exchange goods or data.”<br>**Standard LSP (L3):** “We want to combine goods, data, and our customers. AM would naturally fit in very well. We can receive the goods, we can receive the data, and we can combine everything. At the end, there will be a final distribution of the manufactured parts by whomever.”<br>**Contract LSP (L6):** “We have acquired an AM machine manufacturer as our customer that sells AM machines on the European market and has us as an LSP at its side. We take care of the transportation of AM machines, the spare parts, the powder, and so on.”<br>**Contract LSP (L6):** “We are in charge of ordering the spare parts for the AM machines, the powder […] and that is an opportunity to learn directly.” |

## Complementors

Table A4-15: Representative quotes for Complementors.

| Source | Representative quotes |
|---|---|
| Publicly available information | **HHLA:** “HHLA […] expects to gain accelerated access to the AM market […] allowing the firm to offer its customers more logistics services related to AM […].” (Wolff, 2020)<br>**Andreas Schmid Logistik:** “By bundling of core competencies in industrial AM, supply chain management, and product life-cycle management, we are able to offer unimagined potentials for our customers.”(bu:st, 2018) |

*Table A4-15 continued.*

| | |
|---|---|
| | **Arvato SCM Solutions:** "This collaboration allows us to offer a one-stop-shop solution to our customers, and by doing so we make the benefits of high-quality 3D printing tangible." (Arvato Bertelsmann, 2021)<br>**DSV/Panalpina:** "In return, Panalpina with its global footprint and facilities in major markets can offer Shapeways geographical expansion possibilities and support in logistics, manufacturing, distribution and other value-added services." (DSV/Panalpina, 2016) |
| Interviews | **Standard LSP (L3):** "Due to the great potential of AM, we have acquired a majority share [of the AM service bureau]; now we are active in the AM market, can follow market developments or even shape them to some extent."<br>**Standard LSP (L3):** "We hope that the acquisition will help us to understand the market better. We are all no AM specialists and, thus, need to rely on external expertise. We need support to build a strong market position."<br>**Standard LSP (L4.2):** "The AM machine is not like a food processor that I buy and then it does its job. There is development involved, there are parameter settings involved. So, the AM process is always sold as plug-and-play, and it is if you want to print a Pokémon figure. But if you are manufacturing spare parts for a train, you need know-how. And at the moment, we are in a better position with partners." |

### Intermediaries

Table A4-16: Representative quotes for Intermediaries.

| Source | Representative quotes |
|---|---|
| Publicly available information | **Visagio:** "3D printing [firms] also offer similar services, albeit with more restrictions on the range of technologies available." (Gowans, 2021)<br>**PostNord:** "Our 3D portal makes it as easy to order a 3D print – as simple as shopping in any online store. All you need to do is log in, place an order and then the product is sent to you." (Eastern Trade Media, 2018)<br>**La Poste:** "Along with allowing users access to 3D printing, they will even be offering the opportunity for help, as customers can simply click a button and then ask advice from '3D Advisors of La Poste.' Not only that – they can actually meet with the advisors at their nearest post office for further help onsite." (O'Neal, 2015)<br>**Royal Mail Group:** "It can be prohibitively expensive for consumers or small businesses to invest in a 3D printer, so we are launching a pilot to gauge interest in 3D printing to sit alongside Royal Mail's e-commerce and delivery capability." (Molitch-Hou, 2014) |
| Interviews | **Contracts LSP (L5):** "The platforms are needed, they are important. They will develop very strongly. The challenge is […] to analyze the part and to find the right service provider. Finding the right partner is something that a platform can currently not offer."<br>**Contracts LSP (L5):** "The purchaser ideally does not even know that he sees a 3D printed part on a platform. He just orders a part and sees oh, the delivery time is only two days. Cool! Customer, the delivery time is two days, but it costs three times as much. Is it worth it to you that I purchase the part?"<br>**Contract LSP (L6):** "We have all the data. We know which spare parts we have on stock and when they are retrieved. What are high-runners, what are low-runners? What is needed at which time of the year? If you evaluate all of this, it would be a wealth of knowledge."<br>**Contract LSP (L6):** "I do believe that it is our competence in partner management that enables us to connect all the entities in the supply chain." |

## Appendix G: Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpe.2022.108521.

# 5 Study A.2: Business models for logistics service providers in industrial additive manufacturing supply chains[25]

| | |
|---|---|
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## Abstract

**Purpose** – This study identifies and characterizes generic configurations of business models for logistics service providers (LSPs) in the context of industrial additive manufacturing (AM). A literature-based framework of the AM service supply chain is developed to embed the generic configurations in their supply chain context.

**Design/methodology/approach** – Following an exploratory research design, we conducted 16 interviews with LSPs, their potential partners, and customers for industrial AM services and triangulated our findings with data from public sources.

**Findings** – We find six generic configurations, the LSP as a manufacturer, landlord, logistician, orchestrator, agent, and consultant. We outline how these configurations differ in their required location, partner, and targeted customer segment.

**Practical implications** – The current discussion of reshoring and shorter, decentralized AM supply chains confronts LSPs with the challenge of how to outweigh losses in their traditional services and stay competitive. This study offers guidance for managers of LSPs by suggesting how the configurations fit the features of specific types of LSPs and by creating awareness for their supply chain implications.

**Originality/value** – This study contributes to the scarce literature on AM business models with in-depth empirical insights on LSPs. By taking a business model lens, we set the ground for theorizing about the business model configurations, in particular, their value creation, value proposition, and mechanisms for value capture.

**Keywords:** Third-party logistics service providers, Industrial additive manufacturing, 3D printing, Business model, Value creation, Digital supply chain

**Paper type:** Research paper

## 5.1 Introduction

Current supply bottlenecks and the COVID-19 pandemic put pressure on firms to reduce vulnerability and exposure to risks in their global supply chains (SCs). For instance, McKinsey (2020) expects that firms will reshore up to one-fourth of the global SCs within the next five years, that is, relocate their manufacturing activities from low-cost countries to Europa and the US to increase their resilience to crises. Industrial additive manufacturing (AM) technologies are recognized as key technologies that have the potential to enable and foster reshoring.

[25] The manuscript of the article has been slightly modified to ensure consistent format and style throughout this thesis. Note that the pronoun “we” is used in this chapter to refer to the authors of the article.
[26] As a result of the review process, a revised version of the manuscript was published. The chapter presented here shows the submitted version that was under review at the time of thesis submission.

AM technologies create components by adding material layer-by-layer as specified in the digital design file. The inherently digital AM process is tool-free, highly automated, and based on general-purpose equipment and basic raw material (Durach et al., 2017b; Laplume et al., 2016). With these specific characteristics, AM promotes a simplified SC design. SCs are expected to become shorter, decentralized, potentially less complex, and more resilient. Small-scale production is expected to be established close to or even at the point of demand, in particular for stand-alone applications like spare parts (Braziotis et al., 2019; Khajavi et al., 2014). However, such a shift from global to local and decentralized AM SCs directly challenges the inherent business models of logistics service providers (LSPs) that possess the assets and competencies for transporting, storing, and handling the global flows of products for their industrial customers.

LSPs are currently confronted with the question of how to stay competitive and balance losses in their traditional logistics services in digital AM SCs (Hofmann & Osterwalder, 2017; Öberg, 2019). Several LSPs have started to enter the AM market with novel services: UPS installed polymer 3D printers in currently 19 UPS stores (UPS, 2022). DSV/Panalpina partnered with Shapeways to offer "logistics manufacturing services", that are, AM and logistics solutions from a single source. While Shapeways provides in-depth AM know-how, DSV/Panalpina contributes with logistics, manufacturing, and other value-added services to this novel offer (DSV/Panalpina, 2016). Moreover, Schenker announced in 2018 its digitalized, platform-based AM service that matches and assigns customer orders of AM parts to a network of selected and qualified partners from the AM domain (Schenker, 2018). A related example is Amazon whose patent for on-demand 3D printing services for consumers was granted in 2018. Their novelty lies in 3D printing orders mobile in the delivery truck (Amazon Technologies, 2018).

The examples demonstrate that LSPs offer combined manufacturing and logistics services with partners (e.g., DSV/Panalpina) and develop digital services with little relation to their traditional logistics services (e.g., Schenker). Furthermore, AM business models seem to be permeable as retailers (e.g., Amazon) intend to become combined manufacturers and LSPs. Motivated by these facets of emerging AM business models from practice, this study aims to develop generic business model configurations of LSPs for industrial AM. By adopting a configurational perspective, we understand a generic business model configuration as a cohesive and clearly distinguishable pattern of how LSPs can create and capture value in digital AM SCs. We embedded our exploration of such configurations in the industrial AM context, hence, where AM is needed for applications like new parts, spare parts, prototypes, and tools. Consequently, we do not target business models on the less demanding end-consumer side of AM technologies (e.g., polymer 3D printing services in UPS stores). To guide our study, we formulated an exploratory research question:

> **RQ:** *How* can LSPs position themselves with generic business models in industrial AM SCs?

We addressed the research question with an inductive qualitative research approach. We conducted 16 in-depth interviews with LSPs and their potential partners and industrial customers and developed six generic AM business model configurations directly from our collected data: We find that LSPs can stay true to their roots by offering logistics services for industrial AM (*logistician*) and by using their relationship-building competencies to establish AM clusters at strategic hubs (*orchestrator*). LSPs can leverage their decentralized warehouses by additively manufacturing for their industrial customers as a value-added service (*manufacturer*) or by attracting AM service bureaus as contract manufacturers for the same reason to these locations (*landlord*). Finally, LSPs can operate in unfamiliar terrain by offering digital, platform-based AM services (*agent*) or consulting for AM (*consultant*), which are not based on their traditional logistics competencies and assets.

Our findings contribute to the nascent research stream of AM business model research. The operations and supply chain management (OSCM) community calls for research that explores how established concepts and models are infused by digital technologies (Goldsby & Zinn, 2016; Olsen & Tomlin, 2020; Stank et al., 2019), partly related to LSPs (Hofmann & Osterwalder, 2017). More concretely, existing work has explored AM business models for incumbent manufacturing firms (e.g., Bogers et al., 2016; Savolainen & Collan, 2020a) and new entrants from the AM domain (e.g., Holzmann et al., 2020a; Holzmann et al., 2020b; Kwak et al., 2018; Rayna et al., 2015). Our study enriches this body of knowledge with an in-depth perspective on LSPs. By applying a business model lens, we foster initial theorization about the developed six generic business model configurations. In addition, we embed our findings in the AM service literature (e.g., Chaudhuri et al., 2019; Rogers et al., 2016) by positioning the configurations in the AM service SC.

From a managerial perspective, our findings offer LSPs direct guidance for integrating industrial AM into their operations. We suggest that the configurations are suitable for specific types of LSPs and raise awareness for their applicability in scenarios of reshoring and potentially shorter, decentralized SCs.

This study is structured as follows. Section 5.2 introduces our theoretical background and reviews relevant OSCM literature to distill the AM service SC. Thereafter, we describe our methodological approach in Section 5.3. In Section 5.4, we derive and characterize six generic AM business model configurations. Section 5.5 discusses our theoretical contribution with a business model lens, outlines managerial implications, and presents our conclusions.

## 5.2 Theoretical background

### 5.2.1 Business model research for additive manufacturing

We understand a business model as a "system-level, holistic approach to explain […] how firms do business" (Zott et al., 2011, p. 1019). A business model provides a coherent framework for the commercialization of products and services (Chesbrough & Rosenbloom, 2002). The business model research commonly addresses three central components of a business model: The *value creation* constitutes how a firm and its partners utilize their resource base (i.e., their assets and competencies) to create and deliver value to the customer (Cachon, 2020). Firms develop a "dominant logic" of value creation, that is, an internally consistent theory or "successful recipe" for value creation that is embedded in their organization (Prahalad, 2004, p. 172). The *value capture* describes the mechanism of generating incoming revenue flows from the value offered to customers (Dubosson-Torbay et al., 2002). The value addressed in both components is embedded in the offerings of a firm, the *value proposition*, that is available to a specific target customer segment (Chesbrough, 2010). To concretize the perceived customer value, we build on the framework of Amit and Zott (2001) who find four value drivers in e-business: novelty, lock-in, complementarity, and efficiency. We postulate similarities in digital dominance between e-commerce and AM.

We use the term *configuration* for a generic AM business model that is suitable to be established across multiple LSPs. Traditionally, a configuration refers to organizational entities that are characterized by a set of dimensions that appear in coherent, mutually supportive patterns (Miller, 1986). The configurational approach expects organizations to create a fit to changes in their external environment while they are also challenged to maintain internal consistency. In this vein, this study implies that AM is a novel source of misfit for LSPs' traditional business models. By aligning their internal structures and, thus, their mechanisms for creating and capturing value (i.e., their resource base and revenue model) to the external customer demand for novel AM services, new or adapted business models may emerge, as similarly proposed by Prockl et al. (2012) for LSP business models in general.

## 5.2.2 Logistics service providers and additive manufacturing

Firms commonly outsource their logistics functions (Langley et al., 2021). LSPs are the organizations that manage, control, and carry out logistics services on behalf of these customers (Delfmann et al., 2002). The logistics market is a competitive one, and LSPs are forced to constantly adapt their services to their customers and strive for service innovation (Flint et al., 2005). Although the impact of AM on LSPs' traditional business models is not entirely manifested yet and lacks empirical validation (Boon & van Wee, 2018; Dong et al., 2021), the OSCM literature emphasizes that LSPs' traditional business models are affected by AM (Öberg, 2019) and the global trend of reshoring and distributed, small-scale manufacturing (Purvis et al., 2021). Existing work recognizes the need and urge of LSPs to change and re-invent their traditional business models (Chen, 2017; Jiang et al., 2017). However, visions of AM business models for LSPs remain conceptual and based on the analysis of scenarios (Holmström & Partanen, 2014; Pause & Marek, 2019). Noteworthy, we identified several studies that envision LSPs to turn into manufacturers in AM SCs (Durach et al., 2017b; Öberg, 2022; Rehnberg & Ponte, 2018), by offering manufacturing services in their warehouses (Chen, 2017), mobile AM in trucks (Ryan et al., 2017; Verboeket & Krikke, 2019), or local AM in hubs close to the final customer (Boon & van Wee, 2018; Öberg, 2019). More concrete investigations include Hecker (2021) who proposes a methodology for LSPs to develop new services, using the AM service development as a use case. Furthermore, Friedrich et al. (2022a) take a process-based perspective to provide an overview of how LSPs currently respond to AM. They establish that different types of LSPs approach AM differently.

In this study, we focus on the outcome of LSPs' current experimentation with AM services, hence, on emerging "complete" AM business models for industrial customers that are expected to enable LSPs to create and capture value from their activities. In addition, we aim to consider the full spectrum of different types of LSPs and build on previous classifications to differentiate between *standard LSPs*, *contract LSPs*, and *consulting LSPs*. The three types are aligned with the practically relevant distinction between second-, third-, and fourth-party LSPs (2PLs, 3PLs, and 4PLs).

In a nutshell, standard LSPs, also termed 2PLs, provide basic logistics services (e.g., transportation, transshipment, and warehousing) that are directly tied to their assets (e.g., their transportation fleets and locations) and not adapted to customer requirements (Sink et al., 1996). Their services are highly standardized, modular, and limited in their scope. Moreover, their operations are typically based on economies of scale, arm's-length relationships, and reflect customers' cost-cutting motives (Prockl et al., 2012; Stefansson, 2006). Contract LSPs or 3PLs, on the other hand, provide highly customized, interaction-oriented services with a long-term focus. They increase their commitment and integration with customers over time (Hertz & Alfredsson, 2003). Consequently, contract LSPs deliver unique, complex service bundles that are rather competence- than asset-oriented and typically include value-added services (e.g., management, information-related, and analytical services) to complement basic logistics services (Prockl et al., 2012; Stefansson, 2006). Consulting LSPs or 4PLs manage other LSPs to provide comprehensive and customized SC solutions. They commonly do not own any physical assets but integrate the competencies of consultants, IT managers, and technology providers into highly customized and complex services (Win, 2008).

By considering the outlined spectrum of services, we highlight four traditional features that LSPs can bring to AM: First, LSPs fulfill the role of middlemen in SCs. By outsourcing their logistics functions to LSPs, industrial customers value the neutrality of LSPs (Hertz & Alfredsson, 2003). Second, LSPs operate close to their customers, and this enables LSPs to gain direct knowledge about their customers' processes and insights into their data (Carbone & Stone, 2005). Third, given LSPs' customer proximity, their organizations and, hence, their locations are highly decentralized and are – particularly for standard LSPs – likely to contain strategic infrastructure nodes such as airports, ports, and terminals (Busse & Wallenburg, 2011). Fourth, LSPs are willing to adapt to their customers and develop competencies in value-added services outside their traditional service scope. Specifically, it is common that contract LSPs even provide light manufacturing and assembly services (van Laarhoven et al., 2000).

### 5.2.3 Service opportunities in additive manufacturing supply chains

Since the first commercially available AM technologies in the late 1980s, numerous AM-related services have emerged (Beltagui et al., 2020; Rong et al., 2018). AM-specific contract manufacturers, termed AM service bureaus, have started to offer manufacturing services combined with various auxiliary services at an industrial scale (Chaudhuri et al., 2019; Rogers et al., 2016). Moreover, specialized suppliers, for example, online AM platform providers, AM consulting firms, and design bureaus have grown the market (Bugdahn et al., 2019; Kwak et al., 2018; Rayna et al., 2015). Currently, industrial AM technologies are in an emerging stage of rapid technological development as reflected in the recent average ten-year (2011–2020) market growth rate of 25.7% (Wohlers Associates, 2021b). The market is a nascent one and this dynamic setting is characterized by heterogeneous and overlapping service bundles. In Table 5-1, we disentangle the single service "bricks" from the OSCM literature and structure them regarding the necessary resource input (i.e., assets and competencies) of service providers. LSPs may be candidates to offer these services, and the overview provides insights into the requirements.

Based on Table 5-1, Figure 5-1 presents the AM service SC. It spans from the procurement of AM machines and materials to the AM design process, the manufacturing process, and the distribution of AM parts to industrial customers. In addition, overarching consulting and support services are aimed at industrial customers who implement AM in-house.

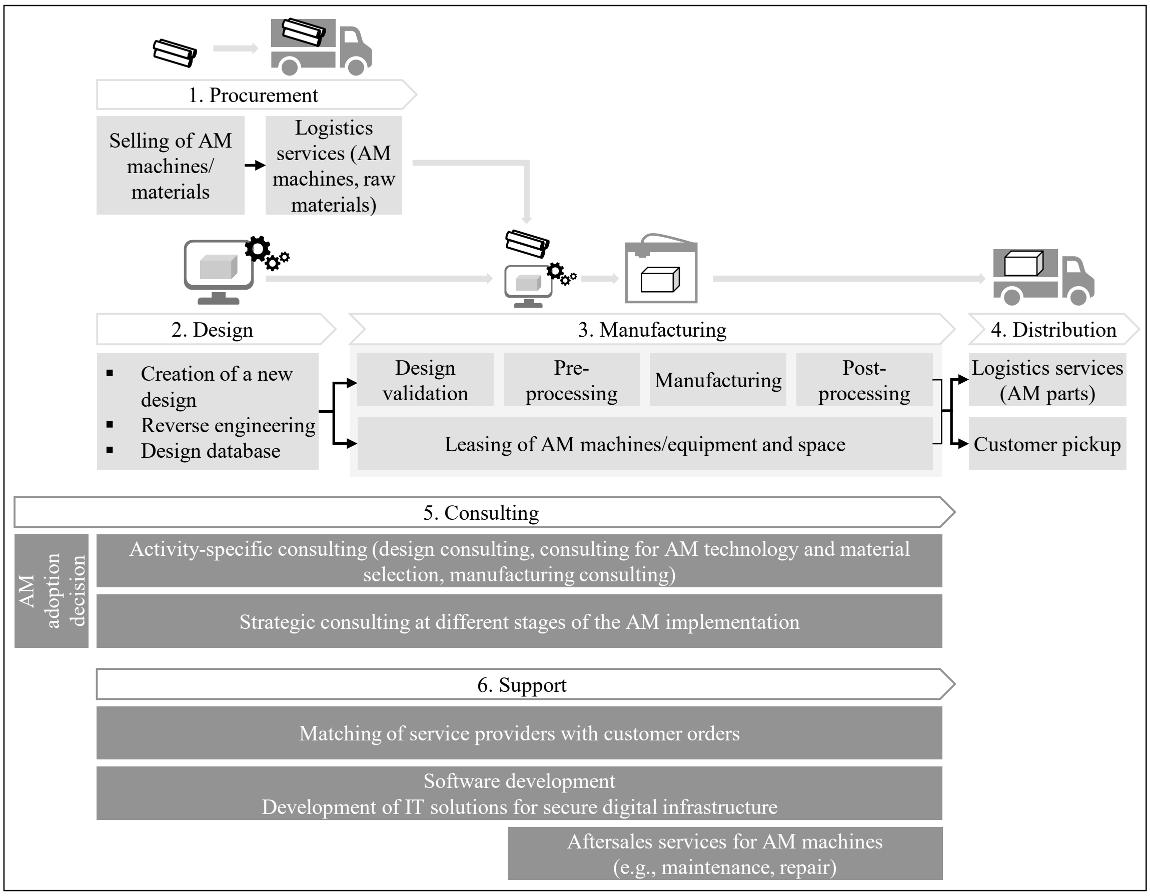



Figure 5-1: AM service SC.

Table 5-1: AM service "bricks".

| AM service | Service description | Required assets | Required competencies | Representative references |
|---|---|---|---|---|
| 1. Procurement | ▪ **Selling of the hardware for AM** (AM machines and materials) via an online platform/marketplace or offline (e.g., at a shop) | Online platform/ marketplace or physical store | AM market expertise (knowledge about AM machines/materials) | Holzmann et al. (2017); Rayna et al. (2015) |
| | ▪ **Logistics for raw materials, AM machines, pre- and post-processing equipment, and related spare parts** (e.g., warehousing, packaging, and transportation) | Logistics infrastructure (e.g., transportation fleets, warehouses) | Logistics expertise, ability to orchestrate an efficient transportation network | Holmström and Partanen (2014); Sasson and Johnson (2016); Verboeket and Krikke (2019) |
| 2. Design | ▪ **Creation of a new design or redesign of an existing 3D model** according to customer requirements<br>▪ **Or: reverse engineering** (duplication of a physical part via 3D scanning and optimization/correction)<br>▪ **Or: offering of access to a 3D model design database** (e.g., for uploading, searching, sharing, and downloading designs) | Design software, 3D scanner, 3D model database, secure digital infrastructure | AM design know-how, 3D scanner know-how, IT/programming skills for setting up and operating an AM design database | Bogers et al. (2016); Eyers and Potter (2015); Kwak et al. (2018); Rayna et al. (2015); Rogers et al. (2016) |
| 3. Manufac-turing | ▪ **Design validation** (e.g., assessment of manufacturability, error control, modifications)<br>▪ **Pre-processing** (e.g., support structures, file conversion, slicing, positioning in the build volume, data transfer to the AM machine, machine setup)<br>▪ **Manufacturing** (e.g., monitoring, cooling after completion of the build)<br>▪ **Post-processing** (e.g., removal of support structures, cleaning, heat/surface treatment, testing/quality control, additional machining, assembly) | Digital infrastructure/ software for design validation and pre-processing, AM machine, tools and equipment for post-processing, manufacturing location | AM design and manufacturing process know-how, IT expertise, in-depth AM machine expertise, planning/scheduling competencies, technical know-how for post-processing | Eyers and Potter (2015); Holzmann et al. (2017) |
| | ▪ **Or: leasing of AM machines/equipment and space** (e.g., booking of time slots for the AM machines/3D printers; offering of access to AM machines and equipment; potential combination with design validation and pre-and post-processing services) | AM machines/3D printers, physical location (e.g., a shop/workshop) | Planning competencies, consolidation of demand, AM machine/equipment and maintenance expertise | Rogers et al. (2016); Sasson and Johnson (2016) |

*Table 5-1 continued.*

| AM service | Service description | Required assets | Required competencies | Representative references |
|---|---|---|---|---|
| 4. Distribution | ▪ **Logistics for finished AM parts** (e.g., warehousing, packaging, and transportation) | Logistics infrastructure (e.g., transportation fleets, warehouses) | Logistics expertise, ability to orchestrate an efficient transportation network | Ben-Ner and Siemsen (2017); Holmström and Partanen (2014); Rauch et al. (2016); Verboeket and Krikke (2019) |
| | ▪ **<u>Or:</u> enabling of customer pickup** of AM parts | Physical location | - | Rogers et al. (2016) |
| 5. Consulting | ▪ **Activity specific consulting:**<br>– **AM adoption decision** (e.g., economic evaluation, feasibility study, identification of AM applications)<br>– **Design consulting** (e.g., training/education for AM (re-)design)<br>– **AM technology and material selection** (e.g., quality and applicability of specific AM machines/materials, compatibility of materials/AM machines)<br>– **Manufacturing consulting** (e.g., training, calibration of AM machines, process optimization/adjustment)<br>▪ **Strategic consulting** (e.g., manufacturing strategy for AM, manufacturing location decision, in-house AM versus outsourcing, supplier selection) | - | AM market expertise, AM design know-how, technological AM machine/material expertise, AM process know-how, customer know-how | Bugdahn et al. (2019); Chaudhuri et al. (2019); Holmström and Partanen (2014); Kwak et al. (2018); Öberg (2019) |
| 6. Support | ▪ **Matching of service providers with customer orders** (e.g., selection of AM design and/or manufacturing service providers, forwarding of customer orders)<br>▪ **Software development** (e.g., for the design/manufacturing process)<br>▪ **IT solutions for secure digital infrastructure** (e.g., intellectual property (IP) rights management, blockchain-based file transfers)<br>▪ **Aftersales services for AM machines** (e.g., maintenance and repair with mobile service teams) | IT infrastructure/online service platform, tools and equipment for aftersales services | AM market and technical expertise, IT/programming skills | Chaudhuri et al. (2019); Kurpjuweit et al. (2021); Rayna et al. (2015) |

## 5.3 Methodology

### 5.3.1 Research design and context

As research on AM business models for LSPs is scarce and AM technologies are at an emerging stage of high uncertainty, an initial, grounded understanding of LSPs' market approaches is needed. Therefore, we selected an exploratory qualitative research design and collected data from multiple sources and perspectives to achieve a strong substantiation for the business model configurations. We embedded our study in the industrial AM context with a need for high-quality AM parts for the applications of industrial customers. Data were collected via semi-structured interviews and enriched with public information from web searches.

Overall, we followed the methodological guidance provided by Gioia et al. (2013) for inductive qualitative research and theorized directly from our collected real-world data, thus, developed configurations of generic AM business models for LSPs as patterns in our data evolved. The AM service SC (see Figure 5-1 and Table 5-1) allowed us to contextualize identified configurations and gain transparency about the required resource base. However, it did not form the entry point into our exploratory study. Moreover, we applied methodological practices of grounded theory as advocated by Corbin and Strauss (2015).

### 5.3.2 Sampling approach and data collection

We aimed at building a heterogeneous sample of firms to discover shared and contrasting patterns of emerging AM business models for LSPs. Therefore, we purposively maximized the variety of perspectives on AM business model configurations of LSPs as our units of analysis (Bell et al., 2019): We approached LSPs that have started to tackle AM and are in the process of shaping and implementing an AM business model. Besides, we opted to integrate the perspectives of manufacturing firms that can reflect as customers of LSPs on AM business models. We also targeted AM-specific actors as potential partners, suppliers, and/or competitors of LSPs for AM services.

We identified suitable firms for our sample via three sources. First, we sought help from "Mobility goes Additive", an international AM industry network with a focus on the transportation sector. Through collaborative efforts, we got in contact with several manufacturing firms and AM-specific actors. Second, we visited AM industry events (e.g., the annual "Additive Manufacturing Forum") and conducted extensive web searches to identify LSPs that are active in AM. Third, we constantly applied a snowballing approach of following up on interviewees' recommendations.

Our final sample consisted of 15 firms. Among them are seven LSPs, three manufacturing firms, and five actors from the industrial AM domain, including AM machine/material manufacturers and AM service bureaus/platform providers (see Appendix A). All firms have their headquarters in Western Europe with a focus on Germany, as the country's competitive position in the logistics (The World Bank, 2021) and AM industry (Wohlers Associates, 2021b) is suitable for our study. While the sample spans diverse industries and services/products, it is focused on larger firms and, hence, suggests that our findings mostly reflect their perspectives on AM business models for LSPs (see Appendix A).

We conducted 16 interviews in the 15 firms between February 2019 and August 2020, which allowed us to iteratively go back and forth between collecting and analyzing our data. We identified key informants in management positions that are directly involved with AM and sent them a letter of introduction focused on our study's overall topic. We developed an initial interview protocol based on our research question (see Appendix B). Following the recommendation of Gioia et al. (2013), we kept the interview protocol flexible to account for the different perspectives of interviewees and our growing understanding. On average, interviews lasted 52 minutes. Appendix A provides background information for each interview.

We triangulated the interviews with internal data provided by some interviewees and information from public sources. More specifically, we collected publicly available data via web searches on current business models of LSPs, directly from LSPs (via firm websites and press releases) and from third parties (via established AM industry news websites with a broad coverage).

### 5.3.3 Data analysis

We transcribed the recorded interviews and sent them to the interviewees for content verification. The transcripts with supplemental data resulted in 264 single-spaced pages. Coding was conducted using the qualitative data analysis software MAXQDA. We applied open, axial, and selective coding (Corbin & Strauss, 2015), and Figure 5-2 visualizes the overall process of data analysis. To ensure consistency, we intensively discussed codes among the authors and resolved conflicts; the full coding process was conducted by one of the authors.

Open coding marked our initial step of summarizing segments of our collected data by developing categories. Then, axial coding aimed to group similar categories. As depicted in Figure 5-2, we identified three main dimensions in our data characterizing industrial AM business models: the required location (*where?*), integration of partners (*with whom?*), and targeted customer segment (*for whom?*). We found additional sub-dimensions for the targeted customer segment, including the range of addressed customers, their previous AM experience, and their geographic dispersion, which reflects their need for decentral AM. The final phase of selective coding enabled us to obtain a holistic, high-level view of our developed data structure. Based on the three dimensions and underlying categories, we successively developed six generic business model configurations of LSPs.

We applied a business model lens to interpret the configurations. In addition, we compared the configurations with our collected publicly available data on LSPs' implemented AM business models and mapped them with the characteristics of different types of LSPs to reason on their fit. Overall, the iterative data analysis process revealed significant differences in the perceptions of our three groups of interviewees for the positioning of LSPs in industrial AM (see Figure 5-2). Comparing these perceptions significantly strengthened our understanding of the six business model configurations.

### 5.3.4 Quality measures

Throughout our methodological approach, we accounted for *credibility*, *transferability*, *dependability*, and *confirmability* as measures for qualitative research that are proposed and interpreted by Halldórsson and Aastrup (2003) for logistics research. Credibility was ensured by basing our study on a clear research framework (i.e., the theoretical business model lens and derived AM service SC from the OSCM literature) and by positioning our findings within this framework ("pattern matching") in Section 5.5. We addressed transferability by reasoning on our selected research approach. In addition, we detailed our sampling logic and study's context by communicating that our findings mostly represent the views of larger, Western European firms. Moreover, we focused on dependability by following the identical approach for each interview, including the use of a semi-structured interview protocol and a standardized data collection and storing process. Finally, we paid attention to confirmability by triangulating data from multiple sources of evidence (i.e., from interviews, internal documents, and public sources). We established a "chain of evidence" by multiple rounds of reviewing transcripts, intensive discussions of codes, and comparing the derived generic business model configurations with examples from practice.

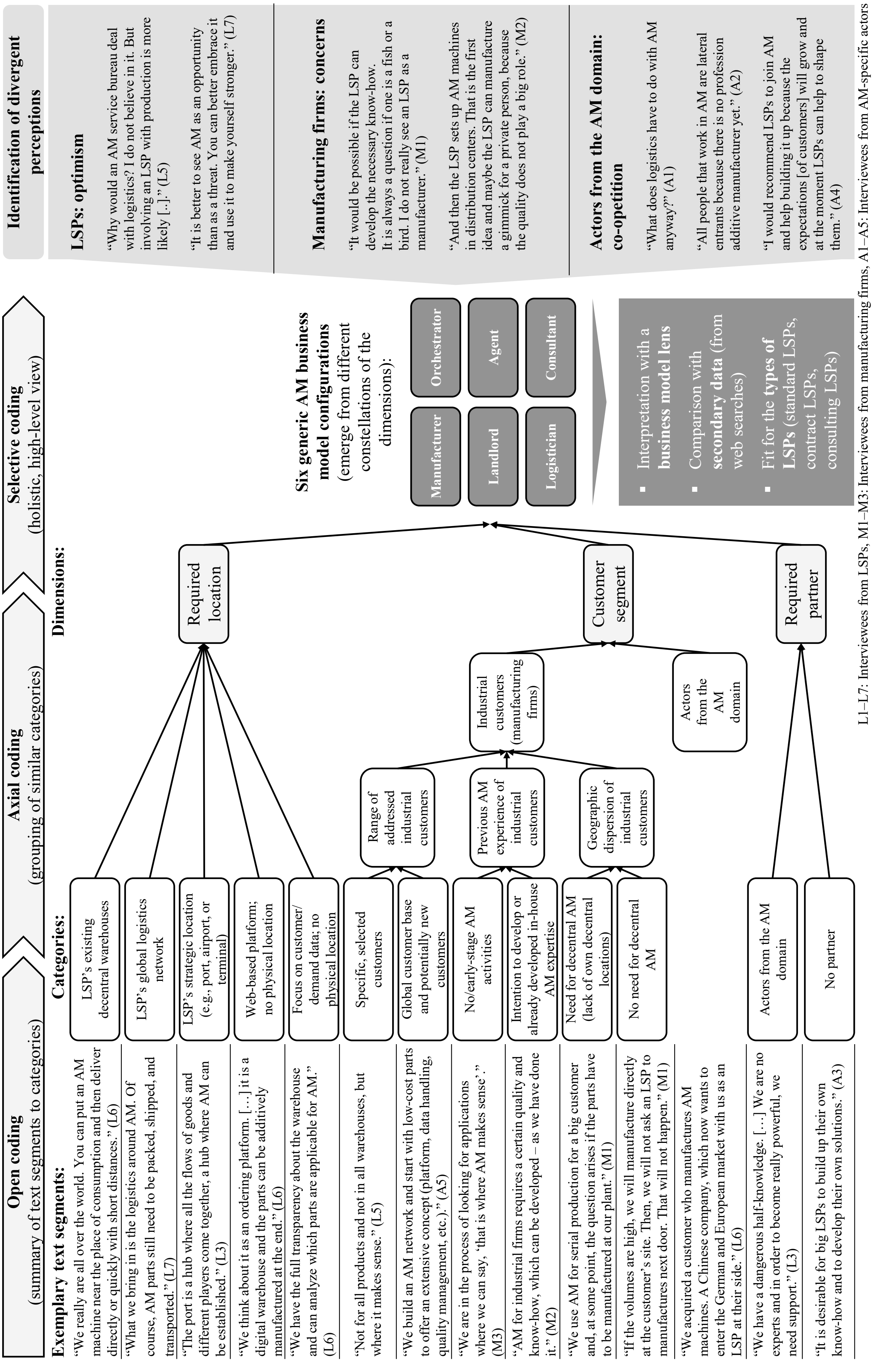



Figure 5-2: Overview of the process of data analysis.

## 5.4 Findings

We found different perceptions of LSPs, manufacturing firms, and actors from the AM domain, as shown in the exemplary quotes provided in Figure 5-2: We experienced that the majority of LSPs approach AM positively with a mentality of not missing the chance to learn and position themselves in the novel market. We further noticed that LSPs partly take a reactive role and perceive it as their customers' responsibility to drive emerging AM technologies toward maturity and demand them to become active in AM. In contrast to LSPs' optimism, manufacturing firms reacted reservedly and questioned whether LSPs can build the specific production know-how for industrial AM. They rather envision LSPs' business models in the consumer 3D printing market. From actors from the AM domain, mixed responses fostered our impression of co-opetition, thus, of simultaneous cooperative and competitive tendencies (Gnyawali & Park, 2011). In this sense, multiple arguments emphasized currently low market entry barriers for lateral entrants, including LSPs. However, particularly AM service bureaus expressed their lack of understanding and reluctance toward LSPs' AM services.

In light of these different perceptions, we extracted three dimensions and underlying categories from the axial-coding process to develop six configurations of generic AM business models: the LSP as a *manufacturer*, *landlord*, *logistician*, *orchestrator*, *agent*, and *consultant*. Table 5-2 summarizes the six configurations in relation to the three dimensions. Four configurations directly depend on the LSP's locations while two are mostly independent of these assets. Furthermore, four configurations target selected industrial customers of the LSP; the other two either target the LSP's global customer base or actors from the AM domain. Finally, two configurations rely on AM specialists as partners.

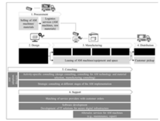
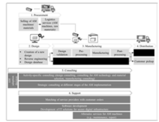
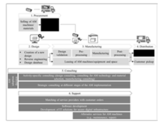
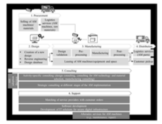
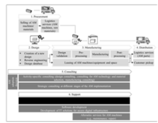
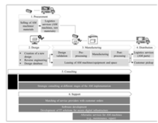
Table 5-2 assigns the generic business model configurations to the AM service SC. As evident, all services are covered by the configurations except for the selling of AM equipment. The following six sections characterize the six configurations of generic AM business models individually and highlight the specific perceptions of our interviewees with representative quotes.

### 5.4.1 Manufacturer

LSPs as manufacturers for AM was the most controversially discussed configuration in our interviews. LSPs use their existing decentralized locations (e.g., warehouses and distribution centers) to co-locate AM, in line with the literature-based vision of LSPs as manufacturers (e.g., Durach et al., 2017b; Öberg, 2022; Rehnberg & Ponte, 2018). With that, LSPs actively contribute to the decentralization of manufacturing activities. For instance, Schenker operates a global network of about 2,100 locations (Schenker, 2022), hinting at the immense potential to decentralize. AM becomes a value-added service that enables a manufacturing postponement strategy for existing customers, as reflected in the literature (Holmström & Partanen, 2014; Purvis et al., 2021; Wieczorek, 2017). In line with this, one LSP emphasized, "Who has the worldwide capacities and who is closest to the customer? If the customer does not want to additively manufacture himself, then, the LSP will do it."

The manufacturer configuration enables LSPs to rely on existing resources (e.g., locations, infrastructure, and employees), which facilitates synergies with administrative and last-mile logistics services. Moreover, it holds the potential to reduce inventory at LSPs' warehouses, for example, by integrating AM into existing repair services. One LSP expressed, "We are at our customer's site and do repairs. If the right part is missing, we can 'print' it immediately and install it."

Table 5-2: Generic AM business model configurations for LSPs.

| Configuration | Description of the generic business model | Dimensions: Required location | Dimensions: Customer segment | Dimensions: Required partner | "Bricks" of the AM service SC (Figure 5-1) | |
|---|---|---|---|---|---|---|
| Manufacturer | The LSP additively manufactures parts with AM machines with existing employees (including (re-)design for AM and the necessary pre- and post-processing steps) | LSP's existing decentral warehouses | Selected industrial customers with no/early-stage AM activities and need for decentral AM | No partner | Design, manufacturing, distribution (logistics) |  |
| Landlord | The LSP leases space to AM service bureaus and handles all AM-related administrative and planning processes as well as last-mile logistics services. The AM service bureau is in charge of the design and manufacturing process, including pre- and post-processing and quality assurance | LSP's existing decentral warehouses | Selected industrial customers with no/early-stage AM activities and need for decentral AM | AM service bureaus | Manufacturing (leasing), distribution (logistics)<br>Partner: Design, manufacturing |  |
| | The LSP leases space to its industrial customers and supports them with all AM-related administrative and planning processes and with last-mile logistics services | LSP's existing decentral warehouses | Selected industrial customers with the intention to develop AM in-house and the need for decentral AM | No partner | | |
| Logistician | The LSP offers logistics services (e.g., warehousing, packaging, transportation) for AM machines, spare parts, and raw materials and/or last-mile logistics solutions for finished AM parts | LSP's established logistics network | Actors from the AM domain and global customer base of the LSP/potentially new customers | No partner | Procurement (logistics), distribution (logistics) |  |
| Orchestrator | The LSP orchestrates an AM industry cluster at a strategic infrastructure node to establish complete AM SCs for consolidated regional demand | LSP's strategic location (e.g., a port, airport, or terminal) | Actors from the AM domain | No partner | Coordination of the overall AM service SC |  |
| Agent | The LSP operates an online AM service platform to store digital designs ("digital warehouse") and transfers customer orders for AM parts to a network of selected and audited AM service bureaus | Web-based platform; no physical location | Global customer base of the LSP/potentially new customers with prior AM experience (available designs/3D models) | AM service bureaus, AM software/platform providers | Support (matching)<br>Partner: Manufacturing, distribution (logistics) |  |
| Consultant | The LSP advises customers that implement AM in-house and offers parts screening (e.g., inventory analysis, identification of suitable applications for AM, scanning, design consulting, and technology/material selection) | Focus on customers' inventory/demand data | Selected industrial customers of the LSP with no/early-stage AM involvement | No partner | Consulting (AM adoption decision, design, procurement) |  |

However, this configuration is overshadowed by concerns about whether LSPs are sufficiently trained and qualified as contract manufacturers for industrial AM and upfront (re-)design activities. LSPs may have gained experience with light traditional manufacturing and assembly services, but we heard multiple times from manufacturing firms that AM is significantly more complex to handle. For example, one manufacturing firm highlighted, “If you want to additively manufacture for industrial customers, it requires a certain quality and a certain know-how that you must acquire.”

Besides, industrial AM is currently asset-intensive and requires additional equipment for pre- and post-processing (e.g., for quality testing, subsequent traditional machining, and heat and surface treatments). There is a broad range of AM technologies and materials, but each application requires a specific choice. Utilizing such a specific investment decentrally poses a great challenge. Noteworthy, AM machine manufacturers offer short-term leasing agreements for AM machines to reduce the risk of capacity utilization and technological obsolescence.

### 5.4.2 Landlord

As a hybrid variant of the manufacturer configuration, LSPs could rent out space in their existing warehouses to AM service bureaus. LSPs emphasized in our interviews that such partnerships are mutually beneficial. They enable AM service bureaus to access new customer segments by decentralizing their (currently centralized) operations without investing in new manufacturing infrastructure. For LSPs, the configuration reduces the required AM-specific resources compared to the manufacturer configuration. For instance, one LSP pointed out, “It is about partnerships […]. We say to all our customers, let us do your logistics because we are the experts. It is stupid if we think that we can be the experts in AM.”

Our interviewees expressed a clear vision of the division of labor between AM service bureaus and LSPs. All technical services such as (re-)design, the production process, and pre- and post-processing, including quality control, are provided by AM service bureaus, while LSPs rely on their in-depth customer know-how for process and data management, production planning, administration, and last-mile logistics services. With that, the business model offers LSPs a low-complexity entry into the AM market and provides the opportunity to learn from partners with the prospect of eventually assuming more AM-specific tasks in the value creation process. This was reflected by one LSP who described a timeline: “I offer you the space first, you do not need to build new production sites everywhere. And if you want, maybe after five years, you can also save the labor costs. When you have manufactured long enough, we can say, ‘Okay, I can do that for you, too.’” Finally, similar cooperative business models may emerge with industrial customers of LSPs that have AM experience and serve a decentral customer base but lack their own facilities close to these customers (e.g., for repair services), as differentiated in Table 5-2.

### 5.4.3 Logistician

The literature mentions bulk transportation of basic raw materials and the last mile of AM parts as logistics services for AM (Ben-Ner & Siemsen, 2017; Rauch et al., 2016). Specifically at decentralized locations, the pooling of transportation is limited and efficient logistics solutions are needed (Durach et al., 2017b). Moreover, in settings where AM complements traditional manufacturing technologies (e.g., AM for specific components of traditionally manufactured systems), LSPs and manufacturing firms expect the relevance of traditional logistics services to persist. One LSP proposed, “The classic logistics services will not disappear. Materials and parts will still be shipped around the world and AM will only enable the digitalization of certain components.”

It is a natural assumption that LSPs are best suited to satisfy the need for logistics services in industrial AM. While utilizing their existing assets (e.g., transportation fleets and warehouses) and logistics expertise, LSPs can incidentally observe and assess the AM market. For example, we interviewed one LSP that provides logistics services for a globally operating AM machine manufacturer. The LSP termed the transfer of traditional logistics services into the AM market as "[…] a great opportunity to take a look at the whole market first. We can learn live on the AM market and evaluate how accepted it is." However, AM-specific transportation volumes are currently comparably small due to the technologies' emerging stage, and this limits the profitability of this configuration. Hence, one AM service bureau critically reflected, "We are already a larger AM service bureau and maybe need 20 tons of raw materials for AM per year. That is ridiculous, that is nothing. Nobody needs to start a business model there."

Nevertheless, with growing knowledge of the AM market, LSPs are in a suitable position to expand their services, for example, from the transportation of physical goods to providing secure, digital infrastructure for digitally encapsulated AM designs. This relates to Holmström and Partanen (2014, p. 426) who postulate that LSPs are best positioned in SCs to become such "trusted gatekeepers" for AM.

### 5.4.4 Orchestrator

LSPs can make use of their strategic locations (e.g., ports, airports, and terminals) to establish and orchestrate AM industry clusters. With pre-settled industry and actors from the AM domain, complete AM SCs can emerge at a single location and enable rapid shipping of AM parts to the final customer. Firms from the AM domain benefit from the existing transportation infrastructure, energy supply, and high utilization of their equipment as a consequence of consolidated demand, as also highlighted by den Boer et al. (2020). In our interviews, one AM-specific actor termed such regionally distributed AM hubs a more realistic SC design than extreme decentralization, for example, for industrial AM applications that require extensive post-processing.

To orchestrate AM clusters, we found LSPs to extend their traditional ability to connect physical flows between transportation modes and actors to AM SCs. For example, one LSP explained, "We are good at bringing different actors together and mediating between them, and that is what you still need in AM." Interestingly, we experienced that LSPs are aware of the digital nature of AM and consider their resources valuable in this domain. One port operator shared with us, "The port is a node where all flows of goods and actors meet. This is a suitable position for AM. It does not matter whether we exchange goods or data."

### 5.4.5 Agent

With online platform-based AM services, LSPs can offer their broad customer base and new customers easy access to high-quality AM parts manufactured by a network of selected, audited AM service bureaus. With that, LSPs fulfill the role of mediators and partner managers that serve as a single point of contact for their customers. One LSP reflected, "With our competencies in partner management, we connect all the actors from the SC. Therein lie our strengths." This basic idea of mediation is similar to the orchestrator configuration but differs from it in its independence from LSPs' traditional logistics resources. Platform-based services are highly digitalized, and interviewees listed concrete service bundles: LSPs are in charge of receiving customers' digitally available product designs, selecting a suitable AM technology and AM service bureau, forwarding the manufacturing order to the AM service bureau, and supporting services like accounting, tax, and customs. Thus, their services aim to cover the full data handling and administrative processes of AM. As a possible extension, LSPs may offer engineering services (e.g., part identification and design adjustments) and store the design files in a "digital warehouse" for recurrent orders.

Note that this configuration requires LSPs to build and manage a network of affiliated AM service bureaus that is attractive to their customers (i.e., represents a critical mass, diversity, quality, and geographic coverage of AM service bureaus). In addition, it necessitates a platform solution that is either developed in-house or by AM software or platform providers. Hence, in-depth IT expertise and specific AM market know-how are a prerequisite for this configuration. Moreover, the configuration is rather suitable for small volumes since manufacturing firms establish and maintain supplier relations themselves for high volumes (e.g., for serial production). In this sense, an AM software provider emphasized, “For high volumes […] a manufacturing firm would have fixed standards, agreed delivery conditions, and a fixed contact person. But if the manufacturing firm just orders a low volume, the efforts to find the right supplier are high, and then the transaction costs are not proportional to the actual production costs.”

Uncertainty about this configuration arose from manufacturing firms. They perceived increased risks of copying, counterfeiting, and liability issues when their intellectual property (IP) encapsulated in digital design files is transferred by LSPs to potentially unknown third-party manufacturers. A manufacturing firm voiced, “If we order via an LSP, who, in turn, transfers the order to an AM service bureau […], then this is in my opinion too far away from what we need.” Hence, LSPs are confronted with the challenge of securing their customers’ digital IP (e.g., by appropriate contract management and secure digital infrastructure) in their platform-based AM services.

### 5.4.6 Consultant

LSPs can support their customers in their initial evaluation and early-stage in-house AM implementation, including the AM adoption decision, design consulting, and technology/material selection (see Table 5-1). While such asset-light services do not rely on logistics resources, LSPs require AM design and production know-how as well as a comprehensive AM market overview. Hence, “brainpower-based” and “holistic” competencies are required for AM consulting services, as emphasized by Manners-Bell and Lyon (2012). Despite the efforts for developing these competencies, several LSPs argued that their in-depth knowledge of their customers’ inventory and demand data (e.g., high/low runners, the influence of seasonality) put them in a suitable position for AM consulting services. One LSP shared with us, “100% of the customer’s parts are stored in our warehouse. We have full transparency. We can run an analysis to identify which parts are additively manufacturable and maybe ‘print’ test parts to evaluate the potential for the customer.” Another LSP supported this view by claiming, “There is currently a data gap between manufacturing firms and AM service bureaus. The LSPs have all the data, they know what it takes.”

## 5.5 Discussion and conclusion

### 5.5.1 Theoretical implications

AM is one of the recent advancements in digital technologies that put pressure on LSPs’ traditional business to move into the era of digital SCs (Cichosz et al., 2020; Hofmann & Osterwalder, 2017). Our exploratory study proposes six generic business model configurations as viable opportunities for LSPs to enter the realm of industrial AM. The configurations enrich the scarce and largely conceptual AM business model research on LSPs with real-world perspectives. Indeed, by considering the different perceptions of LSPs and their potential partners and customers in AM, we provide a reflective view of business models and shed light on involved advantages and challenges. On this basis, we foster theorization by interpreting our findings with a business model lens. We structure this discussion along the three business model components – value creation, value proposition, and value capture – for each configuration and summarize overarching patterns (see Table 5-3).

Table 5-3: Interpretation of the generic configurations with a business model lens.

| Configuration | Value creation | Value proposition | Value capture | Summarized assessment of the configuration |
|---|---|---|---|---|
| Manufacturer | **Resource input:** Existing logistics resources and investment in AM-specific design and manufacturing resources<br>**Partner:** -<br>**Partner's resource input:** -<br>**Time:** On-demand (make-to-order)<br>**Control:** Full control of the LSP | **Satisfied customer demand:** Decentrally manufactured AM parts<br>**Complementarity and transaction efficiency:** Manufacturing and logistics services from a single source (fast and local, end-to-end service, use of existing "connections" to customers) | **Revenue source:** Manufacturing service as a value-added service; additional source of revenue<br>**Risk:** High upfront investment in AM machines/specific competencies; high risk of obsolescence, and insufficient utilization of manufacturing equipment | Assuming the role of manufacturers puts LSPs at the forefront of AM development but requires a high and uncertain initial investment in AM-specific assets and competencies for the design and manufacturing process |
| Landlord | **Resource input:** Existing logistics resources<br>**Partner:** AM service bureaus<br>**Partner's resource input:** AM-specific design and manufacturing resources<br>**Time:** On-demand (make-to-order)<br>**Control:** LSP cannot control the quality of AM parts; trust in partners is required | **Satisfied customer demand:** Decentrally manufactured AM parts<br>**Complementarity and transaction efficiency:** Manufacturing and logistics services from a combined source (fast and local, LSP as a single point of contact for all administrative/logistics processes related to AM, use of existing "connections" to customers) | **Revenue source:** Required revenue-sharing mechanism for combined logistics and manufacturing service<br>**Risk:** Dependence on AM service bureaus; limited attractivity of the business model for AM service bureaus since they bear the risk of utilization of their resources (AM machines/employees) at the LSP's locations | Outsourcing of the design and manufacturing process reduces LSPs' AM-specific investments and enables a low-complexity entry into the AM market; a gradual growth and development of AM-specific competencies is possible; challenges lie in the attractivity of the business model for AM service bureaus as partners |
| Logistician | **Resource input:** Existing logistics resources<br>**Partner:** -<br>**Partner's resource input:** -<br>**Time:** Recurrent standard services<br>**Control:** Full control of the LSP | **Satisfied customer demand:** Performed logistics services for AM<br>**Transaction efficiency:** Standard logistics services with low bargaining costs; economies of scale through demand aggregation (e.g., bulk transportation of raw materials for AM) | **Revenue source:** Contracts for standard/contract logistics services<br>**Risk:** Limited volumes; AM is still a set of niche technologies and there are many cases where AM will not substitute but complement traditional manufacturing technologies | Low-investment entry into the AM market with traditional logistics services; opportunity to learn live on the AM market and get in contact with actors from the AM domain to develop more AM-specific services from there |

*Table 5-3 continued.*

| Configuration | Value creation | Value proposition | Value capture | Summarized assessment of the configuration |
|---|---|---|---|---|
| Orchestrator | **Resource input:** Existing logistics resources (expertise for managing and connecting flows of goods and data)<br>**Partner:** -<br>**Partner's resource input:** -<br>**Time:** Permanent service<br>**Control:** Full control of the LSP | **Satisfied customer demand:** Provided infrastructure for AM products/services and a coordinated, fast AM SC<br>**Network effects:** Increasing value for members of the cluster with a growing number of members based on opportunities for collaboration, capacity sharing, and growing attractivity of the cluster | **Revenue source:** Fixed fees/membership agreements for actors from the industrial AM domain<br>**Risk:** Limited acceptance of actors from the AM domain; slow/stagnated growth of the cluster limits its attractivity | LSPs can leverage their traditional competencies in connecting flows of goods and data by establishing AM clusters at their strategic locations; fast growth is necessary to foster the attractivity of such clusters for actors from the industrial AM domain and encourage their settling |
| Agent | **Resource input:** AM specific-resources (AM market overview) and IT resources<br>**Partner:** Affiliated AM service bureaus, possibly AM software/platform providers<br>**Partner's resource input:** AM-specific manufacturing resources and software/platform solutions<br>**Time:** On-demand orders of AM parts; permanent storing of designs in "digital warehouse"<br>**Control:** Limited control over the quality of AM parts and logistics services (selected, audited AM service bureaus); risk of IP/liability issues | **Satisfied customer demand:** Delivered high-quality AM parts from a network of selected AM service bureaus<br>**Network effects and novelty:** Increasing value of the platform with a growing number of customers and a variety of affiliated AM service bureaus; stored AM designs in a "digital warehouse" eases recurrent orders | **Revenue source:** Required revenue-sharing mechanism for platform-based service with potentially multiple involved parties<br>**Risk:** High upfront investment in IT resources; slow/stagnated growth of the platform limits its attractivity | LSPs can make use of their traditional strengths as mediators, but they rely heavily on partners for the digital and AM-specific elements of the business model; high upfront investments in IT resources (e.g., AM service platform) and fast growth (critical mass of members and partners) are necessary to generate customer value |
| Consultant | **Resource input:** AM-specific resources (AM market expertise; AM design/machine/material know-how); existing logistics resources (demand/inventory know-how)<br>**Partner:** -<br>**Partner's resource input:** -<br>**Time:** On-demand<br>**Control:** Full control of the LSP | **Satisfied customer demand:** Consulting and decision support for early-stage in-house AM<br>**Complementarity and transaction efficiency:** Suitable combination with logistics (consulting) services; can be based on existing communication channels and data connections (from traditional logistics services) | **Revenue source:** Consulting service<br>**Risk:** LSPs' services may lack acceptance because they do not have a relevant manufacturing background for AM | LSPs need to build AM-specific know-how for AM consulting services to compensate for their lacking manufacturing background; the business model creates the opportunity to combine these services with logistics consulting services |

**Value creation:** The configurations vary in their dependence on the traditional logistics resources of LSPs and AM-specific resources (see Table 5-3). The manufacturer, agent, and consultant configurations require novel, AM-specific resources, which manifests in high upfront investment in assets (e.g., AM equipment, IT infrastructure) and/or competencies (e.g., AM design/machine expertise, IT skills, AM market knowledge). Following Prahalad (2004), the configurations require a different resource base and, hence, can be interpreted as a path-breaking change in LSPs' traditional "dominant logic" in their value creation. While the manufacturer configuration combines AM-specific resources with traditional logistics resources (i.e., LSPs' decentralized locations), the value creation for the agent and consultant configurations is based on intangible, digital-oriented (agent), or knowledge-oriented (consultant) resources.

In contrast, the landlord, logistician, and orchestrator configurations all heavily rely on traditional logistics resources. Therefore, they are path-dependent, closely related variants of LSPs' "dominant logic" in value creation according to Prahalad (2004). Finally, the landlord and agent configurations stand out since they rely heavily on the resources of partners from the AM domain. This dependence limits the control of LSPs over the value creation process (e.g., over the quality of supplied AM parts).

**Value proposition:** The value proposed to customers by the manufacturer, landlord, and consultant configurations is dominated by service complementarities (see Table 5-3), which suggests that the bundling of the services increases the perceived customer value (Amit & Zott, 2001). The manufacturer and landlord configurations facilitate "one-stop shopping" of AM parts and related administrative and logistics services from the LSP as the single point of contact for all customer transactions. Similarly, the consultant configuration enables LSPs to offer combined AM and logistics consulting services. In addition, the complementary services target existing customers of LSPs, which may enhance customer value due to high transaction efficiency (e.g., by using established communication channels and ordering procedures). The logistician configuration is even more focused on efficiency. Standard logistics services for AM are economies of scale-driven and associated with a low risk of opportunism, which entails low bargaining and monitoring costs for customers.

In contrast, the orchestrator and agent configurations exhibit network effects. Hence, the utility of members of industrial AM clusters (orchestrator) or users of AM service platforms (agent) grows with the number of members/users, as suggested by Katz and Shapiro (1985). For instance, with the growing size of AM service platforms, customer requirements are more likely to be met by suitable AM service bureaus and broader services may be offered (e.g., storing of designs in a "digital warehouse" for recurrent orders). Similarly, an established AM cluster increases the opportunities for collaboration and capacity sharing among actors from the AM domain. From the perspective of LSPs, customers are supposed to be "locked in," which marks their engagement in repeated transactions and incentives to maintain or even extend their association (Amit & Zott, 2001). In addition, the agent configuration stood out in our interviews for its novelty, earning LSPs a customer reputation as early movers.

**Value capture:** The landlord and agent configurations differ from the other configurations in that they require revenue-sharing mechanisms between LSPs and AM partners (see Table 5-3). In particular, our interviewees challenged the attractivity of the landlord configuration for AM service bureaus since they must accept the uncertainty in utilizing fixed capacities at the LSPs' decentral locations and are limited in their ability to pool orders. New entrants and incumbents are currently all building competitive positions in fast-developing AM (Öberg, 2019). Therefore, competitive motives may outweigh cooperative ones for AM service bureaus, so they may prefer to maintain their centralized, highly utilized, and profitable production plants and rely on efficient logistics services.

## 5.5.2 Managerial implications

Each generic configuration requires LSPs to make specific choices of partners, customer segments, and resources, particularly their existing locations. By considering the distinct features of LSPs, our interview data, and examples from public sources, we suggest a tentative fit of the configurations for the three types of standard, contract, and consulting LSPs (see Figure 5-3). Several LSPs currently design and experiment with AM business models that are in line with the configurations, as illustrated in Figure 5-3. With the provided mapping, we offer concrete guidance to managers of specific types of LSPs. Moreover, we raise awareness for the underlying SC implications of the configurations.

We suggest for **standard LSPs** the logistician and orchestrator configurations as viable business models based on their high asset dependence. Both configurations emphasize traditional logistics resources and enable these LSPs to take advantage of their global transportation networks and strategic infrastructure nodes.

Logistics services for AM (logistician) are also an obvious entry for **contract LSPs** that comes with the advantage of "learning live" on the AM market. However, contract LSPs' abilities to provide highly customized logistics solutions and build competencies outside their traditional service scope primarily put them in a good position to perform AM (manufacturer) as a value-added service (e.g., Durach et al., 2017b; Öberg, 2022; Rehnberg & Ponte, 2018). Alternatively, the landlord configuration emerges as a collaborative, risk-averse business model variant that holds the opportunity to leverage existing customer know-how.

Furthermore, we see indications that the agent configuration fits contract LSPs and **consulting LSPs** due to its asset-light characteristics and novelty, which, again, requires high adaptability and willingness to address challenges outside the traditional LSP business (e.g., IP and liability concerns). The consultant configuration emerges as a natural path for consulting LSPs to complement traditional logistics consulting services. In addition, it may be a suitable extension of contract LSPs' AM services. Both the agent and consultant configurations emphasize the neutrality of LSPs as an advantageous feature. It sets LSPs apart from AM-specific actors who are more likely affected by technological bias and internal conflicts in their customer recommendations (Bugdahn et al., 2019).

Each configuration has specific SC implications and – based on the tentative mapping of the configurations and types of LSPs – we can provide additional insights (see Figure 5-3):

- The logistician and orchestrator configurations emphasize that there remains a need for basic logistics services of standard LSPs in AM SCs, even though revenue prospects are currently limited. AM may require extensive pre- and post-processing and be only applicable for single components to complement traditional manufacturing. For such cases, regional production hubs at strategic infrastructure nodes emerge as a more realistic SC structure for industrial AM than extreme decentralization that demands LSPs with their traditional service strengths for coordination and up- and downstream logistics services.
- The manufacturer and landlord configurations are compatible with the traditional spare parts business offered by contract LSPs to their customers. For stand-alone spare parts, these LSPs can actively contribute to reshored and decentralized AM SCs by establishing AM in their warehouses.
- The agent and consultant configurations create increasing independence of the physical SC through their digital and knowledge-based services. They offer the opportunity for contract and consulting LSPs to extend beyond their established business.

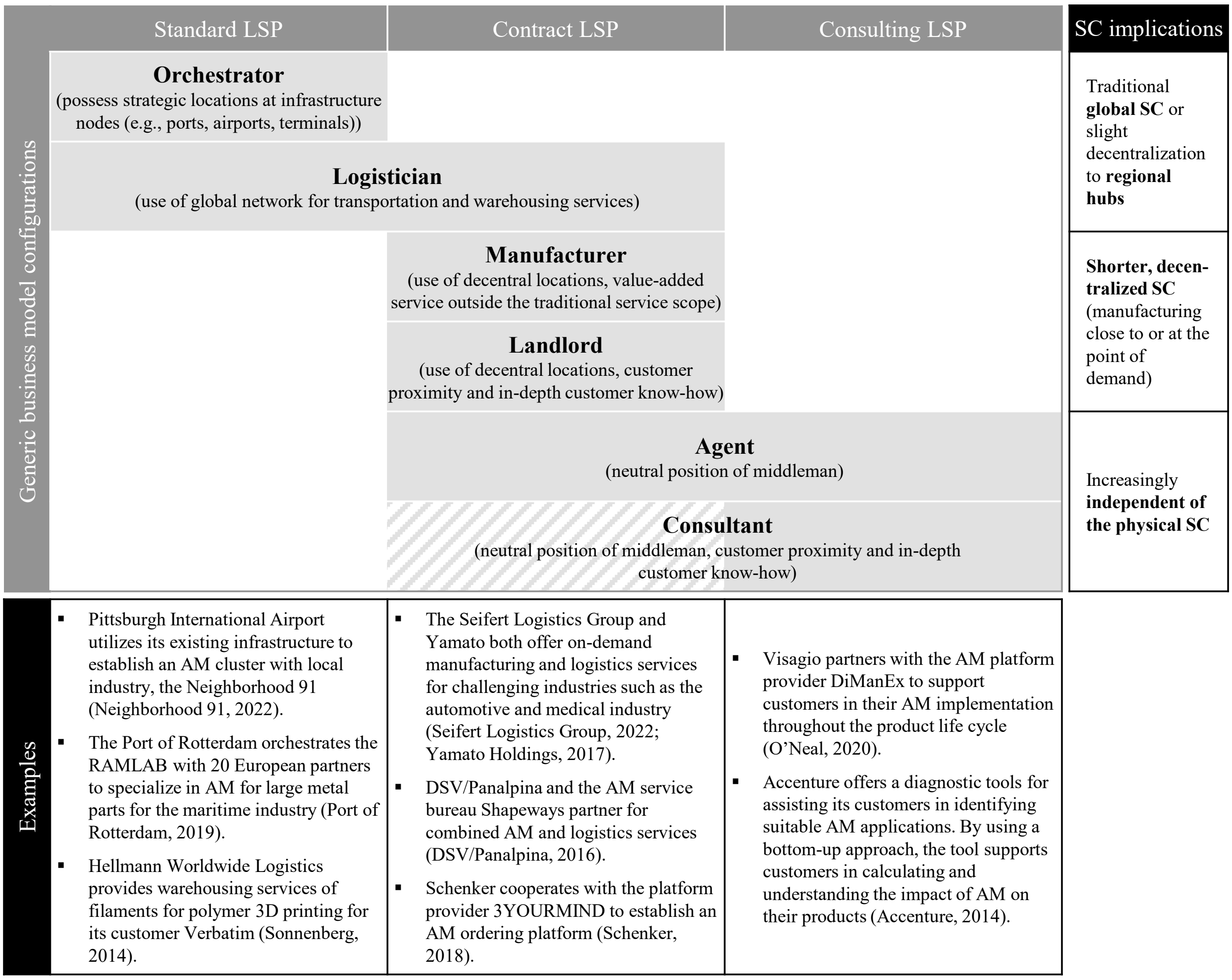



Figure 5-3: Fit of the configurations and their SC implications.

### 5.5.3 Limitations and future research

Our findings are derived from interviews, thus, reflecting the viewpoints of individuals willing to share their ideas. We purposively integrated the perspectives of LSPs, their potential partners, and industrial customers. However, an in-depth investigation of single business model configurations with a case study approach would be a valuable next step to deepen the understanding. In addition, we could not study the particular concerns of small and medium-sized LSPs, which dominate the logistics industry and may have different options for AM business models. However, this will be a feasible extension of our work when AM matures and becomes more widespread.

Furthermore, our study is embedded in the industrial AM context with a need for high-quality AM parts. This focus limits the transferability of the generic configurations to consumer 3D printing. Particularly, courier-, express-, parcel-service providers (e.g., UPS, Royal Mail, and La Poste) have started to test self-manufacturing stations in post offices and offer moderated design platforms, which foster consumer involvement in the design and manufacturing process. Such co-creation activities are less relevant for industrial applications; consequently, future research is necessary to revise and refine the proposed configurations for LSPs' business opportunities in consumer 3D printing SCs.

Finally, in dynamic, nascent markets like the AM market, it is not yet fully clear which resources are strategically valuable and how they can contribute to a competitive advantage (Eisenhardt & Bingham, 2017). As a result, the impact of AM on business models has not fully manifested and competitive positions are not yet established. Currently, we find six generic configurations for LSPs, which we interpret with a business model lens and for which we suggest a fit for specific types of LSPs and their SC implications. LSPs rely on their industrial customers' demand and the participation of AM-specific actors. With that, our study may be the basis for a follow-up, longitudinal analysis of their cooperative and competitive dynamics, which allows gaining further knowledge on how LSPs transform their business in the era of digital SCs.

## Appendix A: Information about the firms and interviews

Table A5-4: Information about the firms and conducted interviews.

| Firm category | No. | Firm description (services/ products) | 2020 annual revenue (millions) | Number of employees (in 2020) | Location of the firm | Interview type | Duration | Job position of interviewee |
|---|---|---|---|---|---|---|---|---|
| Logistics service providers (L) | L1 | Passenger rail transportation | $ 5,000–20,000 | 20,001–50,000 | Italy | Telephone | 0:46 | Network Logistics and Customer Manager |
| | L2 | Passenger rail transportation | $ 500–1,000 | 5,001–10,000 | Germany | Face-to-face | 1:01 | Head of Technical Development** |
| | L3 | Port logistics | $ 1,000–5,000 | 5,001–10,000 | Germany | Face-to-face | 1:01 | Head of Strategic Projects, Economist* |
| | L4.1 | Passenger and cargo rail transportation | > $ 20,000 | > 100,000 | Germany | Telephone | 0:51 | Maintenance Plant Manager |
| | L4.2 | | | | | Video | 0:37 | Technology Scout & Material Expert |
| | L5 | Warehousing; sea, air, and road freight transportation | $ 5,000–20,000 | 50,001–100,000 | Germany | Face-to-face° | 1:07 | Head of Additive Manufacturing** |
| | L6 | Contract logistics | $ 100–500 | 501–5,000 | Germany | Face-to-face | 0:42 | Business Development Industrial |
| | L7 | Transportation services and contract logistics | > $ 20,000 | 50,001–100,000 | The Netherlands | Video° | 0:44 | Head of Contract Logistics |
| Manufacturing firms (M) | M1 | Manufacturer of motor vehicles | n/a | n/a | Switzerland | Telephone | 0:26 | Head of Technical Development |
| | M2 | Manufacturer of rail transportation equipment | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | 0:56 | Vice President Spare Part Services |
| | M3 | Manufacturer of machinery and equipment | $ 100–500 | 501–5,000 | Germany | Telephone | 0:41 | Development and Technical Testing |

*Table A5-4 continued.*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Actors from the AM domain (A) | A1 | AM service bureau with a focus on metal AM ap-plications | $ 1–10 | 1–50+ | Germany | Face-to-face | 0:52 | Managing Partner |
| | A2 | Polymer AM machine manufacturer | $ 500–1,000 | 501–5,000 | Germany | Face-to-face | 0:53 | Technical Consultant |
| | A3 | Metal and polymer AM machine manufacturer | $ 100–500 | 501–5,000 | Germany | Face-to-face | 1:11 | Business Development Manager |
| | A4 | Manufacturer of materials for AM | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | 1:17 | Head of Addi-tive Manufac-turing |
| | A5 | Software provider for AM | n/a | 1–50+ | Germany | Face-to-face | 0:57 | Managing Director |

+ SME.
° Two interviewers present.
* Two interviewees.
** Internal data provided.

## Appendix B: Semi-structured interview protocol (relevant excerpt for this study)

1. *Background information*
    a. Information about the interviewee (name, years in the firm, professional and educational background)
    b. Interviewee's relation to AM (job description, responsibilities, connection to AM)
    c. Information about the firm (firm name, years in existence, size, number and distribution of firm locations, key services/products)
2. *AM business models for LSPs*
    a. Which effects do you expect AM to have on the business of your firm/LSPs?
    b. Can you imagine your firm/LSPs entering the AM market with specific services/products?
    c. Concrete role(s) of the firm/LSPs in AM SCs:
        - Which new or adapted services do you/LSPs (expect to) offer in industrial AM?
        - Which competencies and assets do you/LSPs need (in-house) for these AM services?
        - Which partners do you/LSPs need for these AM services and what is the role of these partners?
        - Can you image your firm/LSPs in the role of a manufacturer in industrial AM (e.g., for spare parts)?
    d. Does your firm/LSPs have a significant advantage/disadvantage in AM compared to other SC actors?
    e. What is special about LSPs?
3. *Wrap up*
    a. What are the critical milestones for future AM development?
    b. If you could change one existing condition/limitation, what would that be?

# Part B

## 6 Study B.1: Make-or-buy decisions for industrial additive manufacturing[27]


| | |
|---|---|
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### Abstract

Much of the potential of industrial additive manufacturing (AM) is said to lie in the digital specification of components that can be transmitted seamlessly and unambiguously to partners fostering flexible outsourcing. In industry, we observe nuanced AM supply chain governance structures that result from make-or-buy decisions, with a tendency to implement AM in-house. Thus, there is a discrepancy between what is discussed in the literature and implemented in practice. We apply a multiple-case study approach to investigate *why* and *how* AM impacts the make-or-buy decision of manufacturing firms. We identify four decision profiles demonstrating the spectrum of specific governance structures and develop a framework to explain the underlying rationales. We find strong arguments for in-house AM including firms' perceived need to protect their digitally encapsulated intellectual property, reevaluation of their core competencies, commitment to internal learning, and senior management's enthusiasm for AM. By using transaction cost economics and the resource-based view, we contribute to the understanding of how arguments of these general theories are modified by the digital and emerging traits of AM. We reveal contradicting guidance in the theories' argumentation for the case of AM and provide managers a clear perspective on alternative strategies for their AM implementation process.



**Keywords:** 3D printing, case study research, digital supply chain, industrial additive manufacturing, outsourcing, supply chain governance


### 6.1 Introduction

Industrial additive manufacturing (AM) is one of the biggest technological breakthroughs in recent years. The fundamental game changer of AM technologies is that parts are manufactured layer-by-layer directly from the digital design file without product-specific setup and tooling (Olsen & Tomlin, 2020). Following recent technological advances, manufacturing firms have started to adopt industrial AM and implement it in their supply chains (Holmström et al., 2016; Holmström & Partanen, 2014). The make-or-buy decision for AM is one essential decision in their AM implementation process (Ruffo et al., 2007). Firms must decide whether they commit resources, including assets and competencies, to in-house AM or if they outsource the AM design and manufacturing process to specialized suppliers, termed AM service bureaus (Hedenstierna et al., 2019).

The specific characteristics of AM are expected to affect or even have a "radical impact" on the make-or-buy decision and, hence, the selected AM governance structure (Rehnberg & Ponte, 2018, p. 59). Yet, limited research exists that explicitly investigates manufacturing firms' make-or-buy decisions for AM. Overall, the broader operations and supply chain management (OSCM) literature puts the vision forward that the digital traits of AM foster flexible, dynamic outsourcing compared with traditionally "analog" manufacturing technologies (Berman, 2012; Hedenstierna et al., 2019; Meyer et al., 2021; Verboeket & Krikke, 2019).

[27] The manuscript of the article has been slightly modified to ensure consistent format and style throughout this thesis. Note that the pronoun "we" is used in this chapter to refer to the authors of the article.

In contrast, current "lighthouse" implementations of AM demonstrate that manufacturing firms opt for more nuanced governance structures than solely short-term outsourcing as proposed by literature: Ernst & Young found in a cross-industry survey of 900 firms that 40% have installed in-house AM technologies compared with 26% that outsource to AM service bureaus and 34% that do not make use of one of the two options yet (EY, 2019). Furthermore, the survey highlighted that 34% of the firms expect that AM will enable the reintegration of outsourced parts and thereby enhance their competitiveness. Indeed, there are famous examples of firms that believe in in-house AM. General Electric has additively manufactured fuel nozzles for its LEAP aircraft engines since 2014 (Kover, 2018). Besides, firms indicate that outsourcing AM is not their long-term strategy. Daimler Buses, for instance, started purchasing spare parts for its buses from AM service bureaus, but recently internalized these parts and established a new AM spare parts business model for cross-industry customers (Automotive World, 2021). In addition, some firms appear to continuously rely on the same outsourcing partners. For example, Boeing contracted an AM service bureau to manufacture FAA-approved structural titanium parts for the 787 Dreamliner on a long-term basis (Scott, 2017).

These examples from practice suggest that some firms pursue in-house (e.g., General Electric and Daimler Buses) and long-term outsourcing strategies (e.g., Boeing) for industrial AM. Hence, their decisions may not be reflected by the arguments for short-term, flexible outsourcing in existing research. Our study is motivated by this discrepancy and the lack of knowledge on why manufacturing firms opt for specific governance structures for AM. Our objective is to gain an in-depth understanding of *why* and *how* AM, as an example of emerging digital manufacturing technologies, impacts the governance choices of manufacturing firms. We address three research questions:

1. Which governance structures do manufacturing firms select to implement industrial AM in their supply chains?
2. *Why* do manufacturing firms opt for these specific AM governance structures?
3. *How* do digital and emerging traits of AM affect firms' governance choices?

In light of the scarcity of previous work on the AM make-or-buy decision, we opted for a multiple-case study research approach. Our collected data reveal four decision profiles for industrial AM characterizing manufacturing firms' current behavior. Beyond a tendency to outsource AM (Waverers), we identify strong efforts to invest in in-house AM (Pioneers), to simultaneously combine in-house AM and outsourcing (Combiners), and an intention to combine in the future (Planners). To investigate the rationales of manufacturing firms (*why*), we draw on two established theories broadly used in the OSCM literature to explain make-or-buy decisions in the "analog" age – namely, transaction cost economics (TCE) and the resource-based view (RBV) (Tsay et al., 2018). We develop a framework to elaborate their established explanations for make-or-buy decisions in the nascent context of industrial AM. Based on this framework, we demonstrate *how* two contextual factors – the digital product specifications and emerging stage of AM – modify general TCE and RBV argumentation and lead to the outcome of the governance decision.

Our findings provide three theoretical contributions. Foremost, we understand our study to be one of the first to investigate manufacturing firms' make-or-buy decisions for industrial AM. Our study contributes to the OSCM literature by structuring and characterizing the four make-or-buy decision profiles and providing insights into the rationales of manufacturing firms, outlined in a set of propositions. Our study thus serves as a reference point for quantitative decision-support models. Second, our study applies a middle-range theorizing (MRT) approach as proposed by Stank et al. (2017), Craighead et al. (2016), and Soltani et al. (2014) for the OSCM community. We contextualize TCE and the RBV to show how the established arguments of these extant theories must be adapted and refined for the novel context of make-or-buy decisions for emerging digital AM technologies, validated with our collected empirical data. Third, our study identifies and characterizes the AM make-or-buy decision as a setting wherein TCE and RBV arguments provide contradicting guidance. We contribute to the understanding of the combination of TCE and the RBV by deriving alternative strategies that manufacturing firms can pursue to resolve the conflict.

From a managerial perspective, our study provides decision-makers in manufacturing firms with a clear perspective on the spectrum of governance choices for industrial AM and raises awareness for alternative implementation paths. Overall, we demonstrate interfaces with the innovation literature and address that our findings are transferable to industries with similar make-or-buy decisions.

The remainder of this paper is structured as follows. First, we embed our study in the extant OSCM literature on industrial AM and combine TCE and the RBV to establish our theoretical lens. Next, we explain the methodology of our multiple-case study approach. Subsequently, we present the four make-or-buy decision profiles of manufacturing firms and use the developed framework to explain their rationales and formulate propositions. The following discussion delineates our contributions to theory and provides managerial insights before we present our conclusions.

## 6.2 Background

### 6.2.1 Industrial additive manufacturing context

Our study uses AM as a prominent example of the shift from traditional manufacturing to direct digital manufacturing (Holmström et al., 2016; Holmström & Partanen, 2014). AM comprises multiple manufacturing technologies. We focus on industrial AM, which refers to the professional application of AM, particularly for metal and high-quality polymer parts. Industrial AM differs from 3D printing, which commonly denotes the consumer side of the technologies (Thomas-Seale et al., 2018). New parts, spare parts, prototypes, tools, and jigs and fixtures are typical applications for industrial AM (Gartner, 2019). With a recent 10-year market growth rate of 25.7% (2011–2020) (Wohlers Associates, 2021b), AM is currently in the emerging stage of becoming an early mainstream market (Gartner, 2019). This stage is characterized by high technological uncertainty referring to the inability to accurately predict technological requirements and environmental effects (Geyskens et al., 2006; Song & Montoya-Weiss, 2001). AM requires two sets of activities, the design processes and the manufacturing processes themselves. Manufacturing processes include data transfer of the digital product specification to the AM machine and pre-processing, the actual manufacturing process, and post-processing (Eyers & Potter, 2015).

### 6.2.2 Literature on the additive manufacturing make-or-buy decision

Previous work extensively discusses the decision to adopt AM versus traditional manufacturing technologies (e.g., Oettmeier & Hofmann, 2017; Schniederjans, 2017; Yeh & Chen, 2018) and identifies barriers to implementation in different industries (e.g., Dwivedi et al., 2017; Mellor et al., 2014; Thomas-Seale et al., 2018). In contrast, the focus of our study lies on manufacturing firms that have already adopted or at least decided to adopt AM and are choosing their implementation paths.

We identified studies that recognize the relevance of the AM make-or-buy decision (Holmström et al., 2017; Rehnberg & Ponte, 2018; Ryan et al., 2017) and that advise firms to carefully assess trade-offs involved in this decision (Verboeket & Krikke, 2019). Berman (2012, p. 157) highlights the “ability to share designs and outsource manufacturing, and the speed and ease of designing and modifying products” as a fundamental benefit of AM. In a similar vein, Manda et al. (2018, p. 2) refer to the outsourcing of AM as a “faster, less expensive and easier route.”

However, the literature that investigates AM make-or-buy decisions remains very limited as of now. Meyer et al. (2021) identify in their review that the AM sourcing literature lags behind practice. From the perspective of manufacturing firms, Hedenstierna et al. (2019) propose a novel bidirectional partial outsourcing model for AM and demonstrate the economic benefits of this governance structure. Their results indicate that the general-purpose characteristics of AM (i.e., no product-dependent setup and tooling) are ideal for flexible outsourcing and facilitate dynamically trading production capacities between alternating contractors and subcontractors. Ruffo et al. (2007) find that in-house AM can be economically advantageous because profit margins and additional warehousing and logistics costs of the outsourcing partner can be avoided by on-demand, in-house AM, whereas Baldinger et al. (2016) calculate comparable market prices and in-house costs. Furthermore, Rogers et al. (2016), Chaudhuri et al. (2019), and Holzmann et al. (2020b) take the perspective of AM service bureaus as predestined outsourcing partners for AM and classify their services. They emphasize that AM service bureaus offer individual service bundles of design for AM, manufacturing, and various auxiliary services such as consulting and training to manufacturing firms. Outsourcing of AM is assessed as a means to eliminate risks (e.g., of technological obsolescence) and is not expected to differ in terms of contractual risks from a “standard manufacturer–supplier relationship” (Rogers et al., 2016, p. 892).

Thus, we note that the extant literature is aware of the AM make-or-buy decision but provides only a few insights into the rationales of manufacturing firms specifically. Nevertheless, many arguments raised in the broader AM research in the OSCM literature have implications for the AM make-or-buy decision and we will interpret them in light of our theoretical lens.

### 6.2.3 Theoretical lens

We focus on the fundamental decision between conducting AM in-house hierarchically (make) versus outsourcing on the free market (buy). The governance structure for AM transactions, market or hierarchy, is the outcome of make-or-buy decisions (McNally & Griffin, 2004; Williamson, 2008). Thus, we purposely omit “hybrid” arrangements like joint ventures, alliances, and acquisitions. Building an understanding for the two polar governance structures, market or hierarchy, is a prerequisite for understanding more complex variants and intermediate forms (see Conner & Prahalad, 1996). Tsay et al. (2018) provide a summary of TCE and the RBV in their review of outsourcing research in production and operations management literature; and we briefly touch on some main points below.

The focus of TCE lies on the efficiency of governance structures. It postulates that governance structures need to be aligned with transaction attributes (Williamson, 1975). Key attributes of transactions are *asset specificity*, *uncertainty*, and *frequency* (Williamson, 2008). Asset specificity refers to the degree an asset can be diverted to other uses. With high asset specificity, the bilateral dependency of the actors involved in a transaction increases along with the potential for opportunistic behavior (Carney, 1998). High risk of opportunism causes contractual arrangements to become expensive, difficult to enforce, and incomplete, forcing firms to implement activities in-house. In the presence of a certain level of asset specificity, high uncertainty requires administrative control and amplifies the trend toward hierarchical governance (David & Han, 2004). However, a number of studies argue that specifically high technological uncertainty encourages firms to remain flexible. Hence, specific types of uncertainty may also result in the need for flexibility that drives firms toward market governance (e.g., Balakrishnan & Wernerfelt, 1986; Folta, 1998; Geyskens et al., 2006). Furthermore, TCE considers the case that asset-specific transactions occur with a high frequency. If so, they require constant and intense monitoring efforts in the market and may be governed more efficiently in a hierarchy (Williamson, 1979).

The RBV takes an alternative perspective on governance structures in arguing that the sustained competitive advantage of a firm results from its individual and superior combination of resources (Barney, 1991). This reasoning implies that firms have largely heterogeneous resources, including all firm-owned assets, capabilities, and knowledge. The RBV suggests that firms are able to create and sustain a competitive advantage with *valuable*, *rare*, imperfectly *imitable* resources and an *organization* that is ready to exploit these resources (Barney, 1995). The concept of core competencies (Prahalad & Hamel, 1990) builds on the RBV and argues that resources which provide a sustained competitive advantage to a firm should not be outsourced to third parties.

It is common and widely accepted that the combination of TCE and the RBV enhances the understanding of the vertical boundaries of a firm (e.g., Hitt et al., 2016; Holcomb & Hitt, 2007; Jacobides & Winter, 2005). Williamson (1999, p. 1098) acknowledges that both theories deal with "partly overlapping phenomena" and emphasizes that firms need to consider their pre-existing strengths (core competencies) and weaknesses in addition to the efficiency of governance structures. Starting from such complementation, Conner and Prahalad (1996) and McIvor (2009) identify scenarios in which both theories stand in conflict. They suggest that given certain combinations of potential for opportunism and resource positions, TCE and the RBV may be contradictory and call for further research to identify real-world settings and gain insights into their implications for theory and practice. Our findings indicate that industrial AM is caught in exactly such a contradictory situation as we will demonstrate in the discussion of our results.

### 6.2.4 Broader literature in light of the theoretical lens

The broader OSCM literature on AM provides arguments that have implications for the AM make-or-buy decision. Table 6-1 summarizes these arguments and interprets them in the light of TCE and the RBV. When interpreted from a TCE perspective, the arguments speak in favor of outsourcing AM. On an aggregated level, this interpretation is based on the assessment of AM machines as general-purpose equipment, location independence of AM, interchangeability of partners, and high technological uncertainty resulting from the emerging stage of AM.

Table 6-1: Aggregated arguments from the broader OSCM literature on AM.

| Topic | Arguments with implications for the AM make-or-buy decision | Key references | Interpretation with the theoretical lens |
|---|---|---|---|
| General-purpose equipment | AM machines are **inherently flexible** to manufacture different designs (no product-dependent setup and tooling) | Chen et al. (2021); Hedenstierna et al. (2019); Holmström and Partanen (2014) | **TCE:** The general-purpose equipment for AM suggests **low physical asset specificity** |
| | The **investment** in AM machines is **not specific for** any **customer or product** | Hedenstierna et al. (2019); Scott and Harrison (2015) | |
| | AM service bureaus can easily achieve economies of scale at fixed setup costs (e.g., for machine warm-up) by maximizing the utilization of AM machines with **pooling orders** from multiple customers | Baumers et al. (2016); Gibson et al. (2015); Holmström et al. (2010); Öberg (2019); Sasson and Johnson (2016) | |
| Location independence | **Low location requirements** for the AM process (ideally only the AM machine and a single basic raw material are necessary at the manufacturing location) | Chan et al. (2018); Durach et al. (2017b); Mellor et al. (2014); Tziantopoulos et al. (2019); Verboeket and Krikke (2019) | **TCE:** The location-independence of AM suggests **low manufacturing site specificity**, but providing a secure digital infrastructure is a practical challenge |
| | **Transportable AM machines** with low space requirements; AM facilitates outsourcing to AM service bureaus **close to the point of demand** | den Boer et al. (2020); Eyers and Potter (2015); Kumar et al. (2020); Westerweel et al. (2021) | |
| | **Digitally encapsulated product specifications** can be seamlessly stored, transferred, and shared with partners | Baumers and Holweg (2019); Berman (2012); Hedenstierna et al. (2019) | |
| | AM requires **secure and robust information and communication technology** for adequate IP protection | Holland et al. (2018); Kurpjuweit et al. (2021); Lacity (2018); Yampolskiy et al. (2014) | |

*Table 6-1 continued.*

| | | | |
|---|---|---|---|
| Interchangeability of partners | Required **know-how** for the AM process is **not specific** | Chekurov et al. (2018); Verboeket and Krikke (2019) | **TCE:** The interchangeability of partners for AM suggests **low human asset specificity** |
| | **Manual intervention for pre- and post-processing** is currently necessary; future **increase in automation** is expected to further reduce the requirements | Khajavi et al. (2014); Roca et al. (2019) | |
| | No dependency on the AM expertise and skills tied to AM service bureaus; partners become **interchangeable** which facilitates **flexible, short-term outsourcing relationships** | Holmström et al. (2016); Meyer et al. (2021); Zijm et al. (2019) | |
| Emerging stage | High **risk of obsolescence** associated with the novelty of AM technologies; requires **cautious investments** in in-house equipment | Hedenstierna et al. (2019); Rogers et al. (2016) | **TCE:** The emerging stage of AM suggests **high technological uncertainty** |
| | Uncertain investment in in-house AM is a **burden** especially **for SMEs** | Strong et al. (2018) | |
| | Outsourcing allows manufacturing firms to **access AM without** initial **high and uncertain investments** (e.g., for AM machines, equipment, training of operators) | Conner et al. (2014); Ford and Despeisse (2016); Mellor et al. (2014); Rogers et al. (2016) | |
| Digital nature | Ease of sharing, modifying, and reusing digital files enabled by AM **reduces the costs of monitoring** a single transaction | Berman (2012) | **TCE:** The digital nature of AM suggests **low dependency on transaction frequency** |
| | **Flexible integration of new outsourcing partners**; on an **occasional or recurrent** basis as long as the digital design file is available | Delic and Eyers (2020); Ruffo et al. (2007) | |
| Available production skills and knowledge | **Easy-to-acquire skills and knowledge** for additively manufacturing a part | Ben-Ner and Siemsen (2017); Chekurov et al. (2018); Fontana et al. (2019) | **RBV:** Available production skills and knowledge suggest that **no competitive advantages** are obtained with additively manufacturing a part |
| | **Little labor input** for the manufacturing process | Chan et al. (2018); Gibson et al. (2015) | |
| | Accessibility of AM for firms **without prior manufacturing background** (e.g., logistics service providers and retailers) | Arbabian and Wagner (2020); Chen et al. (2021); Durach et al. (2017b); Holmström and Partanen (2014) | |
| | **Low market entry barriers** for AM service bureaus | Ford and Despeisse (2016); Holmström et al. (2016); Rogers et al. (2016) | |
| Rare design and software skills and knowledge | Importance of **digital assets and competencies** for AM; focus on AM **design/engineering** and **software skills** | Ben-Ner and Siemsen (2017); Holmström et al. (2016); Massimino et al. (2018); Rylands et al. (2016) | **RBV:** Rare design and software skills and knowledge suggest that **competitive advantages** are obtained with designing a part for AM |
| | Knowledge and skills for AM design are **rare**; a **novel set of skills** and **rethinking of traditional design** are necessary | Mellor et al. (2014); Thomas-Seale et al. (2018) | |
| | **AM service bureaus** are **experienced and capable** of offering design-related services coupled with manufacturing services | Chaudhuri et al. (2019); Rogers et al. (2016) | |
| Core competencies | **Outsourcing** of the AM process is an opportunity to **specialize** and **concentrate on core competencies other than AM** | Holmström et al. (2017); Manda et al. (2018); Rogers et al. (2016); Ruffo et al. (2007) | **RBV:** If AM does not affect **core competencies**, it should be outsourced |

It must not go unnoticed, though, that the wider literature emphasizes adequate protection of firms' intellectual property (IP), which is a concern that comes with outsourcing. Considering arguments that relate to the RBV, the broader literature establishes the differentiation between the physical resources for additively manufacturing a part and the digital resources required for AM design activities. While the former argues in favor of outsourcing the manufacturing process, the latter suggests conducting design activities in-house.

Across the arguments raised in past research, we observe strong points for outsourcing AM activities, even though few aspects are mentioned that warrant in-house operations. Hence, the governance of AM appears to be a scenario wherein TCE and the RBV are mostly complementary, both arguing for outsourcing. However, this anticipation contrasts with prominent examples of in-house AM in industry (e.g., General Electric and Daimler Buses). We start from this thought to identify AM make-or-buy decision profiles of manufacturing firms and investigate their rationales for selecting these profiles with an MRT approach.

## 6.3 Methodology

### 6.3.1 Research design

Our MRT research design builds on the *mechanism + context = outcome* framework as it aims at generating a context-specific understanding, following Stank et al. (2017) and Pellathy et al. (2018). This study is positioned in the growing research field of industrial AM with a need for exploration. It makes use of TCE and the RBV to investigate rationales for make-or-buy decisions in this specific empirical context. We opted for a case study approach that allowed us to explore the novel phenomenon of AM make-or-buy decisions and to continuously interact between TCE, the RBV, and our context-specific data. This constitutes an abductive approach, as suggested by Ketokivi and Choi (2014). We chose a multiple-case, holistic case study design (Yin, 2014). Multiple cases enabled us to draw comparisons, increase the abstraction level, and derive more robust and grounded insights (Eisenhardt & Graebner, 2007).

We defined manufacturing firms, both for components and end products, as our units of analysis as they are confronted with make-or-buy decisions for AM. We aimed at building a deep understanding of the make-or-by decision mechanism directly from the perspective of manufacturing firms. Furthermore, we opted to enhance this understanding by extending and refining the case insights with industrial AM domain knowledge collected from AM-specific supply chain actors. Data collected from the AM domain provided us a rich background and nuanced, context-specific understanding to balance and reflect our case study findings.

### 6.3.2 Case selection

We embedded our study in the context of industries with challenging industrial AM needs. Hence, we focused on regulated industries with high safety concerns, including rail and road transportation, aerospace, and machinery and equipment. All firms involved in our study are located in Europe; mostly Germany. According to Wohlers Associates (2021b), Germany is recognized as a strong contributor to the AM industry, with prominent producers, especially for metal AM systems, being located in Germany. To identify suitable firms, we conducted web searches and contacted a large AM industry network.

We applied replication logic to carefully select the cases of manufacturing firms. Since we focused on the two polar governance choices (market vs. hierarchy), we chose manufacturing firms that we expected to contribute to the emergence of contrasting (theoretical replication) patterns of AM make-or-buy decisions (Eisenhardt & Graebner, 2007; Siggelkow, 2007; Voss et al., 2002). Moreover, we used snowball sampling – namely, following up on interviewees' recommendations – to purposefully integrate cases with extensive experience in industrial AM that we expected to share rich insights into AM make-or-buy decisions, as suggested by Pratt (2009) and Small (2009). The final sample consists of 12 cases of component and end-product manufacturers. All firms are involved in AM and willing to share their insights. As sharing success is easier than sharing failure, we may well over-represent successful AM implementation attempts. Furthermore, the sample contains ten large firms and two SMEs, as a reflection of the novelty of the market (Evangelista et al., 1997; Marzi et al., 2018). Table A6-5 includes further information on the cases.

In addition, we selected 14 firms from the AM domain based on their competitive positions in the nascent industrial AM market. These included eight potential suppliers of manufacturing firms for in-house AM (i.e., AM machine manufacturers, AM material suppliers, and AM software and platform providers), four AM service bureaus as predestined outsourcing partners for AM, and two AM industry experts, all detailed in Table A6-6.

### 6.3.3 Data collection

We collected data via semi-structured interviews between February 2019 and April 2020. Following Dubois and Gadde (2002), we abductively developed an interview protocol (see Appendix B) based on the extant literature on AM and first observed AM implementations from industry. As our main interest rests in manufacturing firms' AM make-or-buy decision and rationales, our interview protocol focused on these topics. We initially developed the interview protocol for our primary interviews with manufacturing firms. As we progressed in our case study, we started to conduct context-specific interviews with actors from the AM domain and successively adapted the interview protocol to their perspectives. All interviewees had to be directly engaged with AM and hold a management position that allowed them to contribute to their firms' AM make-or-buy decisions or reflect as AM-specific actors on such decisions from a strategic perspective.

Interviewees were contacted via e-mail and/or phone. A letter of introduction was sent to the interviewees in advance (Yin, 2014), allowing them to prepare for the interview. We conducted one in-depth interview per firm generally with a single interviewee (see Appendix A). In light of the current emerging stage of industrial AM, we are convinced that we identified key informants in the selected firms. The interviews lasted between 30 and 90 min (51 min on average). Fifteen interviews were conducted face to face at the firms' locations, and 11 interviews were conducted via phone or video call. Two authors were present during seven interviews to increase the conformity of their interview techniques; the authors conducted the other interviews individually. Moreover, some of the interviewees provided additional documents (see Appendix A), which we used, along with supplemental data from publicly available sources (firms' websites, press releases, and articles), to triangulate the interviews.

### 6.3.4 Data analysis

The interviews were recorded, transcribed by the authors, enriched with data from secondary sources, and stored in a case study database. The transcripts were sent to the interviewees to verify the content and to rule out misunderstandings and misinterpretations and were revised if necessary by the authors. The iterative data analysis process overlapped with data collection. In total, we analyzed 419 single-spaced pages of interview and supplemental data applying the three fundamental types of coding from grounded theory – open, axial, and selective coding according to Corbin and Strauss (2015). Two authors conducted the data analysis independently using the qualitative data analysis software MAXQDA. Coding was discussed extensively among the authors, and conflicts were resolved. The described coding approach allowed us to gradually increase the level of abstraction while shifting from analyzing the individual make-or-buy decisions of each manufacturing firm to analyzing across all our cases to gain an in-depth and reflective understanding of their rationales. In this way, decision patterns emerged from multiple steps of analysis and multiple perspectives, in line with what Eisenhardt (1989) proposes for within- and cross-case analysis.

To be more specific, we identified 31 individual make-or-buy decisions by the manufacturing firms and we found three dimensions characterizing these decisions: the pursued strategy (*in-house*, *outsourcing*, *mixed*), the maturity level of the make-or-buy decision (*tentative*, *established*), and the AM application with its associated quality requirements (*new parts*, *spare parts*, *prototyping and tooling*, *education and research*). In addition, we distinguished the applications with respect to the materials (*metal* (*M*), *polymer and others* (*P*)) since metal AM is oftentimes considered to be more technologically challenging than polymer AM. We classified the identified make-or-buy decisions according to the three dimensions as illustrated in Figure 6-1. Note that the firms commonly make various complementary AM make-or-buy decisions, for instance, for multiple products or business divisions. By graphically comparing similar and contrasting characteristics (see Figure 6-1), we arrived at four distinct AM make-or-buy decision profiles of manufacturing firms and used them to structure the results of our within-case analysis.

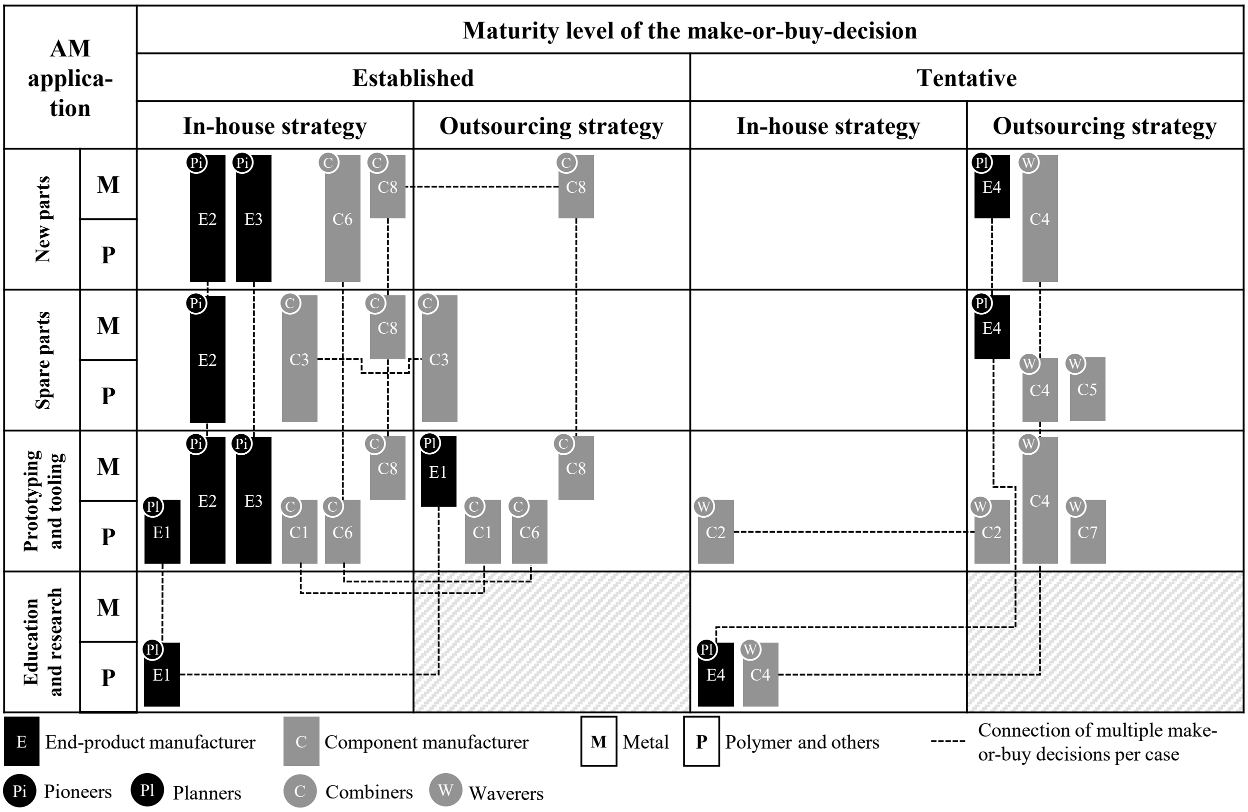


Figure 6-1: Classified make-or-buy decisions of the manufacturing firms.

Following this classification, we developed a conceptual framework across all cases that enabled us to capture the rationales for AM make-or-buy decisions and investigate the explanatory power of TCE and RBV arguments in the context of industrial AM. In doing so, we followed a top-down MRT approach, as suggested by Craighead et al. (2016). We started with general TCE and RBV arguments and used our collected data to substantiate how the industrial AM context modifies the general arguments. In this phase of the analysis, the additional data collected from AM-specific actors was essential to recognize nuances and deepen our contextual understanding of the rationales.

Throughout the process of case selection, data collection, and data analysis, we accounted for rigorous case study design (see Table 6-2), commonly assessed with four criteria: internal validity, construct validity, external validity, and reliability (Cook & Campbell, 1979; Gibbert et al., 2008).

Table 6-2: Quality measures.

| Criterion | Fulfillment | Recommendations from the literature | Measures implemented in this study |
|---|---|---|---|
| Internal validity | Plausible causal relationships and logical reasoning are sufficient to defend research conclusions (Gibbert et al., 2008) | Clear research framework (Yin, 2014) and discovery of underlying theoretical reasons (Eisenhardt, 1989) | Focus on the two polar governance structures (market vs. hierarchy); navigation within TCE and the RBV as grand theories to elaborate context-specific aspects of make-or-buy decisions for industrial AM (MRT approach) |
| | | Pattern matching of empirically observed patterns and predicted or established patterns in previous studies (Eisenhardt, 1989) | Positioning of findings in the extant OSCM literature, as derived in the background section |
| Construct validity | Data-collection process leads to the accurate observation of reality (Denzin & Lincoln, 2017) | Clear chain of evidence (Yin, 2014) | Review of transcripts by authors and verification by interviewees; transcript revision by authors; coding and intensive discussion of codes among authors; classification and framework development based on the coded data |
| | | Data triangulation – use of different data-collection strategies (Yin, 2014) | Collection of data about the cases of manufacturing firms from multiple sources (12 semi-structured interviews); triangulation with internal data and supplemental data (firms' websites, press releases, and articles) |
| External validity | Case study allows for analytical generalization from observations to theory (Gibbert et al., 2008; Yin, 2014) | Cross-case analysis of multiple cases (Eisenhardt, 1989) or a nested approach of multiple cases within a firm (Yin, 2014) | Analysis of multiple cases of manufacturing firms with a transparent and identical approach; classification of the individual behavior of manufacturing firms to four distinct AM make-or-buy decision profiles (within-case analysis) and investigation of the rationales across the cases (cross-case analysis) |
| | | Reasoning for case study selection and details on the context (Cook & Campbell, 1979) | Scarcity of previous work on the AM make-or-buy decision and resulting need for exploration; embedding of case study in industries with an expected need for industrial AM and a broad spectrum of make-or-buy decisions; additional collection of data from actors from the industrial AM domain to reflect the case-study findings and develop a context-specific understanding |
| | | Replication logic (Yin, 2014) | Selection of cases for predicted contrasting AM make-or-buy decisions; complementation with a snowballing approach |
| Reliability | Absence of random errors (Gibbert et al., 2008) and repeatability of results (Lincoln & Guba, 1985) | Transparency by documentation (Yin, 2014) | Development of an interview protocol and standardized data-collection and storing process |
| | | Replication by storing processed data in a case study database for later retrieval (Yin, 2014) | Use of the software MAXQDA to store the case study data and development of a coding system |

## 6.4 Findings

We first present the four make-or-buy decision profiles of manufacturing firms (within-case analysis) before investigating across all cases the rationales leading to the observed behavior in light of TCE and RBV arguments (cross-case analysis).

### 6.4.1 Make-or-buy decision profiles of the manufacturing firms

We identified four make-or-buy decision profiles covering the spectrum of manufacturing firms' behavior for industrial AM: *Pioneers*, *Combiners*, *Planners*, and *Waverers*. Figure 6-2 positions the four profiles according to the three derived dimensions with a focus on the pursued strategy (in-house, outsourcing, mixed). The following discusses the characteristic behavior of each of the four profiles individually.

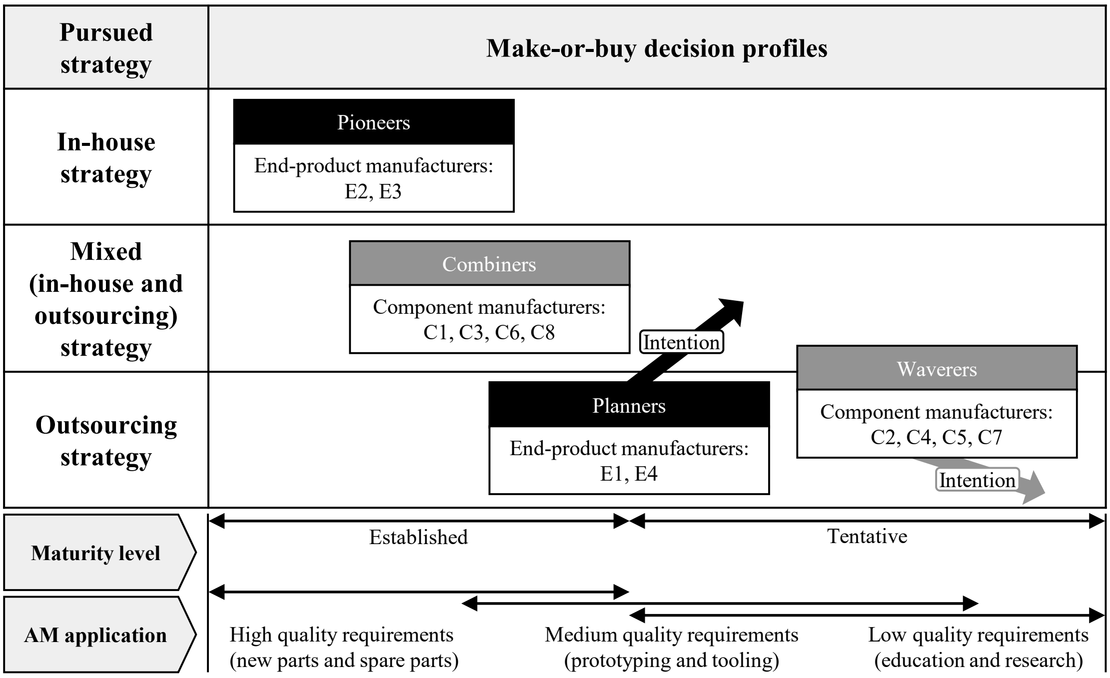


Figure 6-2: AM make-or-buy decision profiles of the manufacturing firms.

*Pioneers* and *Combiners* characterize manufacturing firms that homogeneously pursue established strategies. Their governance choices appear to be deliberate and focused on demanding AM applications with high-quality requirements (see Figure 6-2). *Pioneers* are end-product manufacturers that substitute traditional manufacturing steps with AM. These firms benefit from their early entry into the AM market and operate at the edge of technology by focusing on utilizing AM for the serial production of new parts. Pioneers have identified AM use cases, built the necessary design and manufacturing skills in-house, and are beginning to implement standard processes for AM. These firms now additively manufacture some parts in-house that used to be traditionally outsourced, thereby increasing vertical integration. Based on their expertise and reputation, Pioneers have also established third-party AM businesses dedicated to winning new customers. As of now, Pioneers do not intend to outsource AM in the future.

*Combiners* benefit from combining both in-house AM and outsourcing for specific applications – that is, they apply a make-and-buy strategy. Jacobides and Billinger (2006, p. 249) coined the term "permeable vertical boundaries" for this type of strategy. Besides one SME from the aerospace industry (C8), Combiners consist of large component manufacturers (see Appendix A). These firms rely on extensive experience in industrial AM and have recorded increased vertical integration due to AM. By orchestrating secure firm-owned networks of AM machines and developing specialized units for AM, Combiners demonstrate high integration of AM in their organizations. We observed that Combiners' in-house capacity is reserved for demanding IP-sensitive applications, whereas they outsource to selected, audited AM service bureaus to gain access to specialized and/or rare AM technologies or to overcome peaks in demand that exceed their own AM machine capacity. Combiners plan to expand the mixed strategy in the future. Long-term collaboration with AM service bureaus, just as it is common with traditional suppliers, is their aspired goal for expanding the mixed strategy.

In contrast, *Planners* (partly) and even more so *Waverers* (entirely) represent cases that pursue tentative strategies mostly for AM applications with medium- and low-quality requirements. Their AM make-or-buy decisions are not fully developed yet; therefore, Figure 6-2 shows their status quo and future intentions. *Planners* are end-product manufacturers focused on outsourcing AM. They have established initial relationships with AM service bureaus for pilot applications, but the current use cases do not affect Planners' core business yet. Nevertheless, Planners already have (E1) or are in the process of successively implementing transaction routines (E4) with their initial partners (e.g., for outsourcing metal samples). The initial partners were commonly approached based on geographic proximity or a very preliminary search. However, Planners have a clear vision of establishing strategic outsourcing relationships once their value-creating AM applications are fully identified. They plan to carefully select AM service bureaus for serial production using a tendering process. We further observed Planners' intention to complement outsourcing with in-house AM in the future. Specifically, they initially invested in polymer 3D printers to gain experience and then build their in-house AM expertise from there. Thus, Planners may well develop a mixed strategy in the future.

*Waverers* are smaller component manufacturers than Combiners (see Appendix A). These firms have only recently started AM implementation and pursue a tentative mixed strategy. Apart from prototyping, these firms have not (yet) decided to permanently outsource AM. Waverers work with AM service bureaus on pilot studies, often combined with consultancy for use-case identification and (re-)design for AM. Such initial collaborations may be hindered by financial and time constraints. For example, one component manufacturer indicated, "We did a training with an AM service bureau to qualify our staff in assessing parts for AM, but it was a bit too expensive and time-consuming." Furthermore, Waverers might invest in in-house polymer 3D printers for education purposes and to build trust and acceptance, but they believe developing in-house expertise for demanding applications is not currently feasible. Their reluctance to in-house AM is partly based on disappointing first AM experiences. For instance, one of the Waverers reported that profitable in-house AM for their customers failed, leading to a stagnated usage of the AM machine for internal purposes and no further involvement in AM. Hence, we found Waverers to consider an AM outsourcing strategy as a future direction.

Overall, the four profiles suggest a broad spectrum of governance choices among the manufacturing firms in our sample. All the interviewees from manufacturing firms reflected and argued that their strategy was suitable for their specific situation. Pioneers and Combiners *actively* increase their vertical integration in the transition from traditional manufacturing technologies to AM. Moreover, Combiners benefit from in-house AM and outsourcing. While their demanding IP-intensive applications are governed by hierarchy, more diverse and less demanding (polymer) applications are governed by both hierarchy and market with carefully selected outsourcing partners. Combiners and Planners already have or intend to develop long-term outsourcing relationships with qualified partners, which is similar to traditional manufacturing. Waverers tend to outsource AM although they are hesitant to commit to a permanent AM governance structure, partly due to financial constraints and unfulfilled expectations for initial in-house AM attempts.

### 6.4.2 Framework for additive manufacturing make-or-buy decisions

As a next step of the analysis, we reviewed the perspectives collected across the cases to develop a framework outlining the rationales for AM make-or-buy decisions. For the framework development, we considered the domain knowledge provided by the AM-specific actors. Overall, we extracted multiple consistent influence factors and structured them on two levels, as presented in Figure 6-3. General factors directly lead to the AM make-or-buy decision, and the manufacturing firms' viewpoints can be explained using TCE and RBV argumentation. The general factors include *core competencies*, *IP concerns*, *capacity and skill investment*, and *dependency*. What is more, we observed contextual factors that are specific for AM as emerging digital manufacturing technologies: the *digital product specifications* and *emerging stage of AM*. The contextual factors do not affect the make-or-buy decision directly but do alter firms' emphasis on and understanding of the general factors. In the following discussion, we analyze the effect of the general factors and develop propositions on how the contextual factors modify manufacturing firms' perception of the general factors when it comes to the AM make-or-buy decision. In addition, we reflect the applicability for the four identified make-or-buy decision profiles.

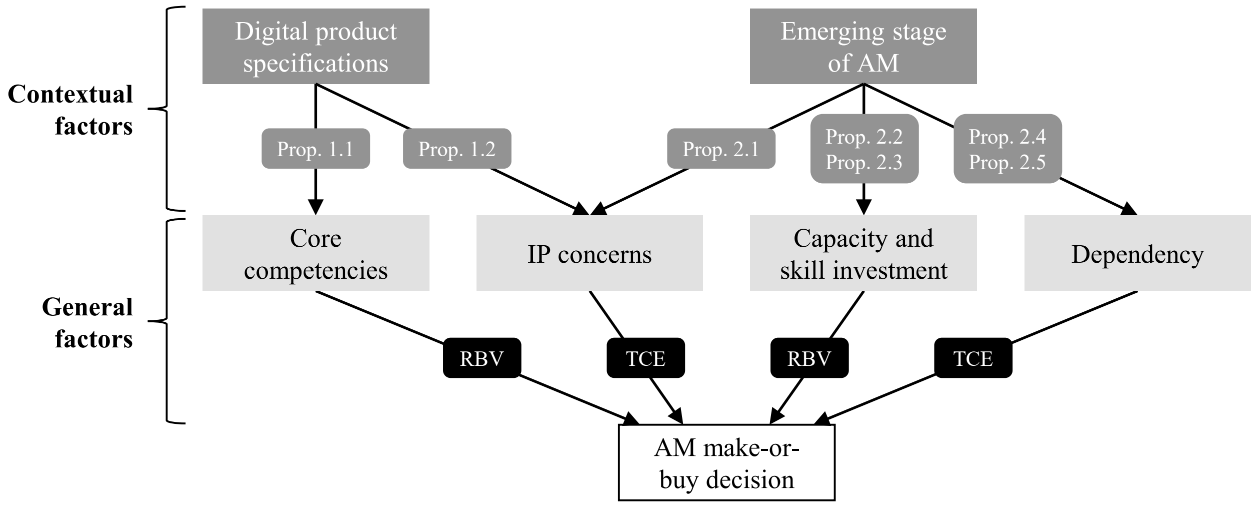


Figure 6-3: Contextual and general factors influencing AM make-or-buy decisions.

#### 6.4.2.1 Core competencies

**General effect**

Interviewees pointed out that radically different and innovative design skills are required to realize the potential of AM supporting literature-based reasoning (see Table 6-1) on manufacturing firms' digital resource position (e.g., Rylands et al., 2016; Thomas-Seale et al., 2018). For example, one component manufacturer shared, "I see design as the value-creating process because all the know-how is linked to design." As suggested by Mellor et al. (2014), the interviewees emphasized that engineers with experience in traditional manufacturing need to acquire new skills for AM design; thus, investments in education for building AM capabilities are required.

Following Prahalad and Hamel (1990) and the RBV logic, the interviewees stressed that they would not be willing to outsource AM design activities that are considered core competencies. We observed that the firms generally do not consider traditional design to be a core competency but tend to consider AM design to be such a competency. Indeed, AM design capabilities are a source of sustained competitive advantage, particularly when design improvements (e.g., lightweight structures, complex geometries, or increased functional integration) are achieved. One component manufacturer pointed out, "The competencies for AM design are rare, and that is why you can differentiate from the market." Following the RBV argumentation, manufacturing firms develop and use design capabilities internally.

**Contextual modification by digital product specifications**

Digital product specifications are central to the AM process. Indeed, the manufacturing firms reported that all their AM knowledge and expertise are encapsulated in digital files. We observed that the perceived relevance of digital product specifications affects the manufacturing firms' core competencies. For example, an end-product manufacturer explained, "The game is decided more on digital than on physical soil." In other words, digital product specifications have led the firms to reevaluate their core competencies.

Most notably, the interviewees emphasized that digital product specifications contain not only design files but also specific AM material and manufacturing-process information (e.g., layer thickness, speed, and manufacturing temperature). As an extension of previous work (e.g., Holmström et al., 2016; Rylands et al., 2016; Thomas-Seale et al., 2018), we found that valuable, rare, and highly protected digital design resources for AM only facilitate superior-quality AM parts when they are combined with capabilities to develop AM materials, and AM machine process parameters. In this vein, one component manufacturer highlighted, "If I have ingenious designs [...] they usually only work in combination with a material and process parameters which I also develop." Similarly, an end-product manufacturer shared, "If you qualify and certify materials for AM parts, then it is, of course, core know-how." Thus, manufacturing firms consider the combination of design, material, and process information to be core competencies for AM.

Following the RBV line of argumentation, this reevaluation of core competencies indicates that hierarchical governance is superior for not only AM design but also for manufacturing activities. The central argument for such full internalization of design and manufacturing activities is that the required material and process expertise can only be developed with extensive experience with in-house equipment, foremost with AM machines. Thus, our observation contrasts with the OSCM literature which emphasizes that outsourcing the AM process is a suitable means to specialize and concentrate on core competencies other than AM (e.g., Holmström et al., 2017; Manda et al., 2018; Rogers et al., 2016; Ruffo et al., 2007). In sum, our interviewees strongly indicated the need to interweave digital and physical resources for pursuing AM in-house.

**Prop. 1.1:** *Digital product specifications of an AM part represent a core competency for a manufacturing firm because value-creating design and rare machine expertise in material and process parameters are combined. Exploiting the full potential of AM encapsulated in digital product specifications, requires mastering activities in the digital and physical domain, thus, internalizing the AM design and manufacturing process.*

This rationale applies to Pioneers and Combiners. It is not relevant for manufacturing firms whose core business is not (yet) impacted by AM (Planners) or for firms pursuing tentative strategies for less demanding applications (Waverers).

### 6.4.2.2 Intellectual property concerns

**General effect**

The majority of the manufacturing firms perceived IP protection for AM to be a practical challenge, in line with literature-based reasoning (e.g., Kurpjuweit et al., 2021; Yampolskiy et al., 2014). In particular, manufacturers with established AM governance structures and demanding applications assessed existing IP-protection systems to be insufficient, leaving them exposed to a high risk of copying and counterfeiting. Indeed, one component manufacturer commented, "Sure, you can protect yourself with all kinds of non-disclosure and cooperation agreements [...] but how can I ensure that the supplier does not start a spare parts business?" These IP concerns brought forward by the majority of the manufacturing firms are a straightforward TCE example of firms' fear of opportunistic behavior by their outsourcing partners. With perceived uncertainty in this domain, the manufacturing firms are unsure how to secure their IP beyond trust and standard development contracts. As a result, potential opportunism increases the need for firms to monitor transactions closely (Williamson, 2008), which can be avoided by in-house AM.

In contrast, we also encountered the opposite viewpoint among actors from the AM domain and component manufacturers tentatively considering AM make-or-buy decisions. These interviewees argued that IP concerns are exaggerated and emphasized that contractual terms and existing IT security technology can effectively protect IP. As such, blockchain technology has been proposed by these interviewees and by the literature (e.g., Holland et al., 2018; Kurpjuweit et al., 2021; Lacity, 2018) as a way to simplify secure AM outsourcing.

**Contextual modification by digital product specifications**

Unambiguous digitally encapsulated design, material, and process specifications can be shared with partners seamlessly, facilitating location-independent manufacturing (e.g., Baumers & Holweg, 2019; Hedenstierna et al., 2019). Previous work expects this advantage to be a cornerstone of outsourcing AM (see Table 6-1), arguing that the ability to seamlessly transfer specifications lowers transaction costs, following the TCE logic (Berman, 2012). However, we observed that the manufacturing firms perceived the presumed advantage of easily sharing and distributing digital files as a source of increased risk of IP loss and, thus, as a barrier to outsourcing. The fear of copying and counterfeiting appears more pronounced for digitally encapsulated AM parts than for traditionally manufactured "analog" parts.

In line with Massimino et al. (2018), we conjecture that the digital encapsulation of AM itself enhances this fear – that is, it enforces general IP concerns and argues for hierarchical governance from a TCE perspective. For instance, one end-product manufacturer shared, "AM is a digital manufacturing technology. Everything digital is easy to copy." The manufacturing firms explained this rationale of increased IP concerns by arguing that copying traditionally manufactured parts is substantially more time-consuming and costlier (e.g., for required tools and specialized machines) than copying digital AM parts. One tentative explanation is that copyright violations are omnipresent for everyday digital consumer products, such as online music, software, and video games (Appleyard, 2015; Kietzmann et al., 2015; Lan et al., 2020), and firms may be extending this fear to AM.

**Prop. 1.2:** *Digital product specifications in AM increase manufacturing firms' IP concerns due to the ease of distributing and sharing digitally available information. The resulting fear that AM is an easy target for copying and counterfeiting strongly argues for in-house AM.*

Pioneers and Combiners are particularly concerned about losing their digitally specified IP in AM. Planners only express it with respect to their intention of outsourcing AM parts affecting their core business in the future. Waverers have not yet obtained significant IP worth protecting; consequently, they have no concerns in this regard. Finally, the actors from the AM domain do not differentiate between digital encapsulation and "analog" availability of sensitive information and, thus, have limited concerns. One AM platform provider drew a noteworthy comparison, "If I outsource milling jobs, I can also outsource AM jobs. I do not see any difference."

**Contextual modification by the emerging stage of AM**

From a technological perspective, emerging AM technologies have not yet reached full automation. To date, manual pre- and post-processing and in-depth knowledge of AM machines and materials are necessary to obtain high-quality parts. The manufacturing firms expect increased automation of the AM process with maturity suggesting low human asset specificity, as also predicted by the literature (see Table 6-1) (e.g., Khajavi et al., 2014; Roca et al., 2019). With that, manufacturing can be unambiguously specified digitally, and the interviewees fear that with properly specified AM material and machine parameters, operating AM machines will become increasingly feasible for non-specialists. Literature-based reasoning positions such potential accessibility of AM for firms outside the industry context as an advantage of outsourcing and an impetus for new business models of actors without manufacturing background like logistics service providers and retailers (e.g., Arbabian & Wagner, 2020; Durach et al., 2017b; Holmström & Partanen, 2014). Low market-entry barriers are expected to allow manufacturing firms to outsource to multiple AM service bureaus (Ford & Despeisse, 2016; Holmström et al., 2016; Rogers et al., 2016).

In contrast, the manufacturing firms in our interviews expressed fear of new competitors with limited industry knowledge but expertise in the digital domain (e.g., with extensive engineering skills) entering the market. With that in mind, one component manufacturer highlighted, “You can look at AM parts in an abstract way, and that opens the door for new players.” The manufacturing firms feel threatened by competitive pressure while there is uncertainty about which firms will succeed once the AM industry stabilizes, as it has been observed in other nascent markets (Folta, 1998). This rationale has resulted in skepticism and limits trust in young relationships. As one component manufacturer put it, “Customers turn into competitors.”

Consequently, we noted the manufacturing firms’ fear of working with AM service bureaus or customers that may use obtained knowledge to support their own independent activities. Thus, sharing knowledge is a barrier in the emerging AM industry; in other words, with potential exposure to opportunism, general IP concerns increase and foster hierarchical governance. We observed this rationale for firms with established AM strategies and substantial IP in AM, that is Pioneers and Combiners, and incipiently for Planners.

**Prop. 2.1:** *The emerging stage of AM increases manufacturing firms’ IP concerns due to their fear of actively creating new entrants to the market. Resulting barriers of sharing knowledge and limited trust in young relationships enhance the perceived risk of opportunism, arguing for in-house AM.*

#### 6.4.2.3 Capacity and skill investment

**General effect**

AM machines require substantial investments, particularly for metal AM. The manufacturing firms pointed out that these financial investments are a burden for SMEs due to their limited financial leeway, as predicted by Strong et al. (2018). In response, AM machine manufacturers emphasized that they offer customized short-term leasing models to overcome this barrier. Once operational, the AM machine needs to be highly utilized in order to run efficiently and we observed that generating sufficient demand is a challenge for the majority of the manufacturing firms. AM service bureaus are in a superior position to pool orders, as suggested by our interviewees and the literature (see Table 6-1) (e.g., Baumers et al., 2016; Öberg, 2019; Sasson & Johnson, 2016).

However, manufacturing firms disagreed with the claims in the literature that AM requires little labor input (e.g., Chan et al., 2018; Gibson et al., 2015) and that production know-how for industrial AM is relatively easy to acquire (e.g., Ben-Ner & Siemsen, 2017; Chekurov et al., 2018; Fontana et al., 2019). To the contrary, operating an AM machine today requires specialized know-how and a wealth of experience. Thus, investments in AM include not only AM machines but also associated costs for personnel training (i.e., to operate the machines), manual pre- and post-processing, maintenance, and repair. The AM machine manufacturers emphasized in our interviews that starting to operate an AM machine is all about experimenting with the machine, often through a trial-and-error approach, stressing that there is no “plug and play” with these machines. In line with this, an AM industry expert shared with us that it takes about nine to 12 months of adjustments until an AM machine operates reliably.

As a consequence, sufficient demand, capacity investments, and intensive skill and know-how development are necessary to operate an AM machine efficiently. These requirements put specialized providers – namely, AM service bureaus – in a stronger resource position than manufacturers. Öberg (2019) finds that AM service bureaus create such imbalance of resource positions to prevent being outperformed by manufacturing firms. Following Barney (2013), AM service bureaus thus have a competitive advantage over manufacturing firms for AM.

**Contextual modification by the emerging stage of AM**

The nascent AM market constantly brings technological development that could potentially render existing machines obsolete. Existing literature acknowledges such high technological uncertainty (Conner et al., 2014; Ford & Despeisse, 2016; Mellor et al., 2014). Hence, the manufacturing firms are afraid to invest in specific AM technologies as technological development may outpace the depreciation of the machines. This scenario would either decrease the firms' returns on their AM investments or reduce the utilization of potentially outdated machines. For example, an AM software provider explained, "We have incredibly fast technological development. This means that the machines need to be depreciated in two or three years [or else] they are not state of the art anymore." From a TCE perspective, with respect to technological uncertainty, the high risk of obsolescence is governed efficiently by the market as this governance structure allows manufacturing firms to terminate relationships and flexibly switch to partners with "updated" technological capabilities. In doing so, they avoid being locked in to an obsolete technology (Balakrishnan & Wernerfelt, 1986; Geyskens et al., 2006).

Despite the risk of obsolescence and the general reasoning for a weak resource position, the manufacturing firms often internalize AM. We observed that senior management's high enthusiasm for emerging AM technologies affects the AM implementation process. Often, senior management believes in the potential of AM, as reflected in the firms' willingness to take higher risks for AM machine investments than for investments in traditional manufacturing equipment. In this vein, one end-product manufacturer shared, "We have the support of the board. 100% capacity utilization is not required. At 50%, we already get the 'go' to buy an AM machine." Our interviewees from the AM domain interpret senior management's risk-seeking as over-enthusiasm for AM. They judge that manufacturing firms may invest too quickly in AM machines with inflated expectations and no clear perspective on potential applications. For instance, an AM service bureau commented, "There is extreme hype about AM. In my opinion, it is a bit of a bubble. AM is a manufacturing technology, but it is not a panacea for all technical problems."

Thus, we propose that the high expectations for AM outweigh the reasoning based on the high risk of technological obsolescence and the current weak resource position. We observed multiple such situations among Waverers. This rationale also applies partly to Planners as they indicate a willingness to accept financial risks for their initial in-house AM investments.

**Prop. 2.2:** *The emerging stage of AM inflates senior managements' expectations for AM. Thereby, it leads manufacturing firms to make risky investments in in-house AM despite a weaker resource position than AM service bureaus and the risk of technology obsolescence.*

Possessing in-house AM machines allows manufacturing firms to learn and to gain engineers' acceptance for AM. Hopkinson et al. (2006) point out that firm culture needs to adapt to AM; convincing engineers is perceived important on this path by our interviewees. Furthermore, gaining AM experience early could help firms outpace their competitors. The manufacturing firms in our interviews expect that building internal expertise before the market stabilizes or consolidates may safeguard their positions and become a market-entry barrier as the industry matures. In addition, outsourcing to AM service bureaus complicates or even prevents a later market entry. One component manufacturer emphasized, "As the customer of an AM service bureau, you learn nothing or only very little. And that is why you are not well prepared to buy an AM machine in the future."

Thus, as a central rationale, the manufacturing firms fear that outsourcing prevents internal learning. Moreover, they believe that investing in developing AM production know-how today is a way to prepare so they can create a future first-mover advantage. For instance, one medium-sized component manufacturer explained, "If we deal with AM today, we are well prepared to serve this […] market tomorrow." This rationale is grounded in uncertainty about the future value of AM. Due to the newness of AM, the manufacturing firms are still scouting to determine if and how AM can generate a competitive advantage in the future. As a result, they respond to the uncertainty with ad hoc trial-and-error learning (Folta, 1998). In a similar vein, Dattée et al. (2018, p. 467) relate such early commitment to "fear of missing the train." Pioneers and Combiners apply this rationale to justify their early market entry. Furthermore, we observed this rationale currently for Planners' intention to combine outsourcing with in-house AM in the future.

**Prop. 2.3:** *The emerging stage of AM drives manufacturing firms to build their AM production know-how in-house to facilitate learning and fill experience gaps before the market stabilizes. Hence, prospects of first-mover advantages prompt manufacturing firms to strengthen their weak resource positions by investing in equipment and skill development.*

### 6.4.2.4 Dependency

**General effect**

Initial outsourcing partners for AM are commonly selected by coincidence or based on their geographical proximity. The latter allows for fast coordination and personal contact, which jointly create trust. Trust is necessary in particular when more demanding AM applications are outsourced and manufacturing firms depend on the quality of parts provided by AM service bureaus. To protect themselves, the manufacturing firms implement supplier-management strategies to cope with dependency. We observed that for demanding applications, the firms carefully select, qualify, and assess AM service bureaus through an in-depth process. For instance, a component manufacturer with an established outsourcing strategy highlighted, "AM service bureaus are audited, selected, […] and then we train our suppliers. So, we do that for AM just like for traditional manufacturing."

The rigorous selection and strategic development of AM service bureaus do not align with the literature-based vision of low human asset specificity allowing for flexible, dynamic outsourcing to interchangeable service bureaus (see Table 6-1) (Holmström et al., 2016; Meyer et al., 2021; Zijm et al., 2019), at least not for demanding applications. Following the TCE logic, it appears that the skills and dedicated human capital invested in AM transactions increase the specificity of those transactions and argue for hierarchical governance (Carney, 1998).

**Contextual modification by the emerging stage of AM**

Santos and Eisenhardt (2009) identify that industry structures and institutions are lacking in nascent markets, and the same is true for AM currently. Notably, standards for quality control, certification of materials and safety-relevant parts, and a clear-cut legal framework including product liability have not yet emerged. Consequently, manufacturing firms need to establish individual arrangements with every single AM service bureau they depend on, which entails extensive communication efforts and monitoring in each outsourcing relationship (Thomas-Seale et al., 2018). One end-product manufacturer drew the comparison, "Every engineer knows that he can redraw to DIN or ISO standards for traditional manufacturing technologies like welding. He does not yet have these standards for AM." An AM material supplier reflected that in his experience, "The manufacturing firms must specify exactly how the AM parts are to be produced […] otherwise they obtain a different manufacturing outcome every time." Indeed, with individually provided specifications and measures for quality control, it becomes costly for manufacturing firms to switch to new AM service bureaus. The costs increase the manufacturing firms' dependency and expose them to partners' opportunistic behavior.

With the manufacturing firms locked in, general TCE-reasoning to internalize AM to avoid opportunistic behavior is enhanced (Holcomb & Hitt, 2007; Williamson, 1971). This rationale applies to Pioneers. They refrain from outsourcing due to their inability to fully specify outsourcing in standard contracts and the resulting unilateral dependency. Yet, industry experts expect Pioneers to use their in-house expertise to draw up effective outsourcing contracts once AM reaches a mature stage. For example, one AM industry expert shared, "Once this technology is qualified, approved, and regulated, it is just a normal manufacturing process, and manufacturing firms will go back to their traditional supply chains with one or more key suppliers that know their business."

**Prop. 2.4:** *The emerging stage of AM entails that individually provided specifications and measures enhance unilateral dependency and lock-ins for manufacturing firms, arguing for in-house AM.*

At the same time, the emerging stage of AM technologies fosters a wide variety of technologies, and materials are developing rapidly. No dominating technologies have emerged as de facto standards yet. It is an immense challenge for manufacturing firms to cover the variety of technologies and materials in-house at this emerging stage. However, AM service bureaus have specialized in technologies and materials. Thus, manufacturing firms may opt for outsourcing in the nascent market to gain knowledge on the multitude of options. For instance, a component manufacturer pointed out, "We have to work with AM service bureaus because there is not just one technology. There is a bouquet of technologies and it is important to know and assess in detail the capabilities of each supplier." And an AM software provider reflected this view when recommending, "I would enter the market with competent partners that have an idea of the range of the technologies – because there are hundreds of processes and material combinations. It is super confusing." In addition, outsourcing allows the manufacturing firms to remain flexible as to a final technology choice. Folta (1998, p. 1011) suggests that the "option of waiting" enables individuals to make informed choices at a later, more mature stage.

Nevertheless, our interviewees are well aware of their unilateral dependency on the supplier. Dependency is accepted by manufacturing firms with a tentative AM strategy and is outweighed by the benefits of accessing specialized knowledge and of postponing investment decisions in the broad range of emerging AM technologies. Manufacturing firms with an established AM strategy emphasize safeguards and develop close, trust-based, and long-term relationships with AM service bureaus. Eventually, their initiatives aim at creating bilateral dependency with mutual lock-ins (Holcomb & Hitt, 2007). Suppliers for AM are supposed to become so-called "tier 0.5 suppliers," underlining the need for even closer collaboration and faster communication than required for traditional suppliers, as suggested by Delic and Eyers (2020, p. 6) and Giffi et al. (2014, p. 9). Hence, we propose that the emerging stage necessitates and fosters outsourcing even though manufacturing firms are aware of their dependency.

**Prop. 2.5:** *The emerging stage of AM lets manufacturing firms outsource their activities despite their dependency on suppliers. Benefits of technological flexibility and knowledge acquisition outweigh the risk from dependency.*

Waverers and Planners rely on outsourcing partners for a low-complexity entry point for which dependency is of limited concern. Combiners cope with the dependency with trustful, closer, and long-term outsourcing relationships. The rationale does not apply to Pioneers as they have built extensive AM know-how and opted for specific AM technologies early. Thus, the specialized knowledge provided by AM service bureaus is of limited value for them and cannot compensate for their perceived dependency resulting from Prop. 2.4.

## 6.5 Contribution to theory

In the following subsection, we embed our results in the extant OSCM literature. Then, we discuss our results from the perspective of TCE and the RBV. Finally, we shed light on the compatibility and tension of TCE and RBV arguments for emerging AM.

### 6.5.1 Operations and supply chain management literature

Our findings on AM make-or-buy decisions extend the scarce literature in this field. As our foremost contribution, we presented four make-or-buy decision profiles of manufacturing firms for industrial AM and developed an in-depth and context-specific understanding for their rationales. With that, we provide novel rationales and both supporting and contrary insights to the existing OSCM literature on AM. Table 6-3 delineates how the four make-or-buy decision profiles emerge from the developed propositions.

We found rationales for both polar governance structures – namely, for organizing AM in-house and outsourcing. The reevaluation of core competencies (Prop. 1.1), the perceived threat of opportunism for digital (Prop. 1.2), emerging (Prop. 2.1) AM, and commitment to learning early (Prop. 2.3) drive Pioneers and Combiners toward in-house AM design and manufacturing activities. In addition, the inability to fully specify AM outsourcing contracts at the current emerging stage strengthens Pioneers' in-house strategy (Prop. 2.4). Combiners differ from Pioneers in that they accept the challenge in specifying contracts as the overwhelming variety in AM technologies and materials necessitates them to complement their in-house strategy with outsourcing (Prop. 2.5). The two rather tentative profiles, Planners and Waverers, neither have sufficient AM volumes and specific know-how for in-house AM nor does AM affect their core competencies. However, both show evidence that the enthusiasm of senior management for the novel AM technologies is a major driver for in-house AM (Prop. 2.2) leading to potentially disappointing initial AM experiences (Waverers).

The identified rationales go beyond what is currently recognized by the OSCM literature on the AM make-or-buy decision (e.g., Hedenstierna et al., 2019; Ruffo et al., 2007) and the AM implementation process (e.g., Mellor et al., 2014; Thomas-Seale et al., 2018). With that, rather than being a natural consequence of AM implementation, outsourcing becomes an active choice for manufacturing firms. In the current emerging stage of AM, outsourcing relationships are certainly not intended to be flexible and interchangeable, but we observed them to be specific and long-term oriented and to involve investments in dedicated human capital. Our observations give rise to follow-up research in the OSCM literature to formalize the concerns observed across our cases. Such research supports decision-makers in making reasoned decisions when it comes to integrating AM in supply chains.

Table 6-3: Emergence of the four make-or-buy decision profiles.

| Contextual factors | Digital product specifications | | | Emerging stage of AM | | | | Summary |
|---|---|---|---|---|---|---|---|---|
| **General factors** | **Core competencies** | **IP concerns** | | **Capacity and skill investment** | | **Dependency** | | |
| **Propositions** | **Prop. 1.1** | **Prop. 1.2** | **Prop. 2.1** | **Prop. 2.2** | **Prop. 2.3** | **Prop. 2.4** | **Prop. 2.5** | |
| **Pioneers** (in-house) | **In-house:** Core competencies in AM; need to master AM design and manufacturing process to generate competitive advantages in AM | **In-house:** Fear of loss of the digitally encapsulated IP; higher risk of copying and counterfeiting than for traditional manufacturing | **In-house:** Increased fear of loss of IP due to unstable relations and unestablished positions in the nascent market | **Not applicable:** Early market entry; sufficient AM applications justify investments in AM capacity and skill development | **In-house:** "Pioneers" of AM; learn today to build engineers' acceptance and experience gaps in AM | **In-house:** Lack of standards for testing and certification; inability to fully specify AM outsourcing contracts | **Not applicable:** Specialized in AM; knowledge provided by AM service bureaus is of little value; cannot outweigh dependency | Develop core competencies in AM with the prospect of first-mover advantages; expected to eventually draw up effective outsourcing contracts for mature AM |
| **Combiners** (mixed) | **In-house:** Core competencies in AM; need to master AM design and manufacturing process to generate competitive advantages in AM | **In-house:** High IP concerns; secure, firm-owned network for IP-sensitive parts; outsourcing only of parts without core know-how | **In-house:** Barriers of sharing knowledge; fear that customers turn into competitors; partners must be carefully selected | **Not applicable:** Early market entry; sufficient AM applications; AM volumes surpass in-house manufacturing capacities | **In-house:** Foster learning; built experience in AM; integration of AM in the organization; aim to outpace competitors | **Not applicable:** Rigorous selection of partners; cope with dependency with trustful, close, and long-term outsourcing relationships | **Outsourcing:** Variety of AM necessitates outsourcing; aim to take advantage of technological flexibility | Expertise in AM is developed in-house, but the variety in AM technologies and materials requires long-term, trustful outsourcing relationships |

*Table 6-3 continued.*

| Contextual factors | Digital product specifications | | | Emerging stage of AM | | | | | Summary |
|---|---|---|---|---|---|---|---|---|---|
| **General factors** | **Core competencies** | **IP concerns** | | **Capacity and skill investment** | | **Dependency** | | | |
| **Propositions** | **Prop. 1.1** | **Prop. 1.2** | **Prop. 2.1** | **Prop. 2.2** | **Prop. 2.3** | **Prop. 2.4** | **Prop. 2.5** | | |
| **Planners** (strive for mixed) | **Not applicable:** AM does not affect core competencies; AM is limited to internal applications such as prototypes, tools, and samples | **In-house:** IP concerns based on the digital nature of AM for intention to establish long-term outsourcing of AM for core products in the future | **In-house:** Slight concerns for intended outsourcing; planned tendering process and auditing of partners to reduce risk of IP loss | **In-house:** Willingness to accept higher financial risks for initial AM investments than for traditional manufacturing technologies | **In-house:** Awareness that in-house know-how is necessary to evaluate AM and to not miss the chance to position in the AM market | **Not applicable:** Only pilots and internal AM applications; routines with initial outsourcing partners are successively established | **Outsourcing:** Dependency is of limited concern; AM expertise of the partner overcompensates dependency | | Start with initial outsourcing as a low-complexity entry but clear vision of strategic outsourcing coupled with in-house know-how development for core products in the future |
| **Waverers** (reluctant, tendency toward outsourcing) | **Not applicable:** AM does not affect core competencies; only initial pilots | **Not applicable:** No significant IP in AM to protect | **Not applicable:** No significant IP in AM to protect | **In-house:** Hype of management; owner-initiated investments without extensive prior analysis; disappointing experiences | **Not applicable:** Development of in-house expertise is currently not assessed as feasible | **Not applicable:** Only outsource first pilots to AM service bureaus | **Outsourcing:** Dependency is of limited concern; no permanent outsourcing relationships are established for now | | Reluctance to positioning in AM after rushed (partly disappointing) initial experiences based on high enthusiasm of senior management for AM |

## 6.5.2 Contextualizing theories for the make-or-buy decision of additive manufacturing

As we navigated within TCE and the RBV, we found arguments consistent with these theories in the domain of industrial AM. By theorizing at the middle range, we can show how the tenor of TCE and RBV argumentation changes based on the digital product specifications and emerging stage of AM that we identified to be specific for the industrial AM context. Thus, we build a context-specific understanding of these theories and contribute to their application for make-or-buy decisions in the digital age, following the call of Stank et al. (2019). Table 6-4 provides an overview of the chains of argument for both theories developed across the framework we illustrated in Figure 6-3. The chains span from the general factors to their modification in light of the contextual factors and summarize the effects of the digital and emerging traits of AM.

Table 6-4: Chains of argument for the AM make-or-buy decision.

| Theory | General factor | Modification by contextual factor | Effect |
|---|---|---|---|
| TCE | *IP concerns:*<br>Manufacturing firms' IP concerns lead to perceived exposure to opportunism, arguing for **in-house** AM | *Digital traits:*<br>The ease of sharing, reusing, and modifying digital assets becomes a threat, strongly arguing for **in-house** AM (Prop. 1.2) | *The digital and emerging traits increase IP concerns* |
| | | *Emerging traits:*<br>Barriers of sharing knowledge and limited trust in young relationships enhance the fear of opportunism, strongly arguing for **in-house** AM (Prop. 2.1) | |
| | *Dependency:*<br>Rigorous selection and strategic development of outsourcing partners increases the **specificity of transactions**, arguing for **in-house** AM | *Emerging traits:*<br>Individual specifications and measures increase unilateral dependency and lock-ins, arguing for **in-house** AM (Prop. 2.4) | *The emerging traits increase dependency* |
| | | *Emerging traits:*<br>Technological flexibility and knowledge acquisition outweigh the risk from dependency, arguing for **outsourcing** (Prop. 2.5) | *The emerging traits force the acceptance of dependency* |
| RBV | *Core competencies:*<br>Design for AM is a core competency and should be conducted in-house; the manufacturing process should be **outsourced** | *Digital traits:*<br>Interweaving of physical and digital resources requires a **full in-house** strategy for the design and the AM process (Prop. 1.1) | *The digital traits cause a reevaluation of core competencies* |
| | *Capacity and skill investment:*<br>Manufacturing firms cannot utilize equipment and skills better than the market; their weak resource position favors **outsourcing** AM | *Emerging traits:*<br>Enthusiasm of senior management and potential first-mover advantages cause manufacturing firms to invest in **in-house** AM to strengthen their weak resource position (Prop. 2.2/2.3) | *The emerging traits encourage capacity and skill investments* |

From a *TCE perspective*, we found the AM make-or-buy decision to be driven by IP concerns and dependency. Both generally argue for in-house AM based on highly specific transactions and the resulting risk of opportunism. In particular, our findings indicate a perceived inability to sufficiently protect IP with currently available technology and standard contracts, and a need for rigorous selection and auditing of AM outsourcing partners. This argues for monitoring transactions closely, high administrative efforts, and individual contractual arrangements. By focusing on the specifics of AM, we found that the digital and emerging traits enhance the TCE arguments for in-house AM (see Table 6-4). The digital traits increase IP concerns based on the perceived ease of copying and counterfeiting digitally encapsulated sensitive information. Likewise, the emerging traits increase IP concerns resulting from the fear of unintentionally creating new competitors in the unstable and fast-moving AM market. Moreover, our results show that the emerging traits increase dependency based on lacking industry guidelines and standards for testing and certification processes. However, technological flexibility and knowledge acquisition appear to necessitate outsourcing despite the high dependency. Thus, the rarity of knowledge and technological variety at the emerging stage force firms into market governance despite high transaction costs. Experienced manufacturing firms with established AM strategies accept and counter the dependency by limiting outsourcing to applications without IP concerns and by aiming for close and ideally bilaterally dependent outsourcing relationships.

From an *RBV perspective*, we identified the definition of core competencies in AM and the commitment to capacity and skill investments to form the fundamental arguments for the AM make-or-buy decision. The arguments for both general factors suggest outsourcing the manufacturing process to AM service bureaus. Their ability to specialize in AM technologies and pool orders constitutes a superior resource position. For manufacturing firms, novel design skills emerged as the predominant source for developing competitive advantages in AM. By extracting the specifics of AM, we found that the digital and emerging traits reverse the general arguments and direct them toward in-house AM (see Table 6-4). The emerging traits trigger firms to reevaluate their core competencies. Following the RBV line of arguments, our results show that firms only feel capable of leveraging AM design skills as a rare, valuable, and imperfectly imitable resource in an interplay with in-house expertise for the physical manufacturing process. Although the importance of digital resources is amplified in AM compared with physical resources (e.g., AM machine and material expertise), both are not decoupled (yet). Whenever AM affects the core business of firms, this coupling explains why firms increase their vertical integration when switching from traditional manufacturing technologies to AM. Besides, the emerging traits have encouraged investments in AM machines to strengthen the weak physical resource positions. Firms make substantial and risky investments with the prospect of reaching resource positions that competitors cannot obtain.

### 6.5.3 Contradicting guidance by theories

Literature-based reasoning suggests that the implementation of AM is a scenario in which TCE and the RBV seem to be complementary. Our study extends this view and provides a more nuanced perspective. As demonstrated in Table 6-4, TCE and the RBV point on the general level to opposite directions (see *general factors*). As a result, many of the manufacturing firms are in a situation where TCE and the RBV give contradicting guidance on whether to outsource or to internalize AM. The firms fear opportunism by AM service bureaus as they are concerned about IP protection and lock-ins in highly specific transactions. At the same time, the key technology expertise remains with machine manufacturers and specialized service bureaus at the emerging stage. Manufacturing firms find themselves in a relatively weak resource position, see Figure 6-4.

In such a situation, TCE raises the argument that manufacturing firms should internalize AM due to the risk of opportunism, whereas the RBV suggests outsourcing due to the manufacturing firms' inferior resource position. Conner and Prahalad (1996) and McIvor (2009) have previously discussed the possibility of such a contradiction. From our study, we note that the majority of the manufacturing firms in our sample are currently opting to resolve this dilemma by investing in in-house capacities and capabilities to strengthen their resource positions. Hence, in the AM context (see *contextual factors* in Table 6-4) manufacturing firms fund in-house capacities and skills to avoid the risk of opportunism. We thus note that TCE arguments aimed at minimizing the risk of opportunism oftentimes outweigh RBV arguments in the case of emerging industrial AM. Only a few experienced manufacturing firms resolve the contradiction by accepting and eventually seeking to reduce the high transaction costs of outsourcing.

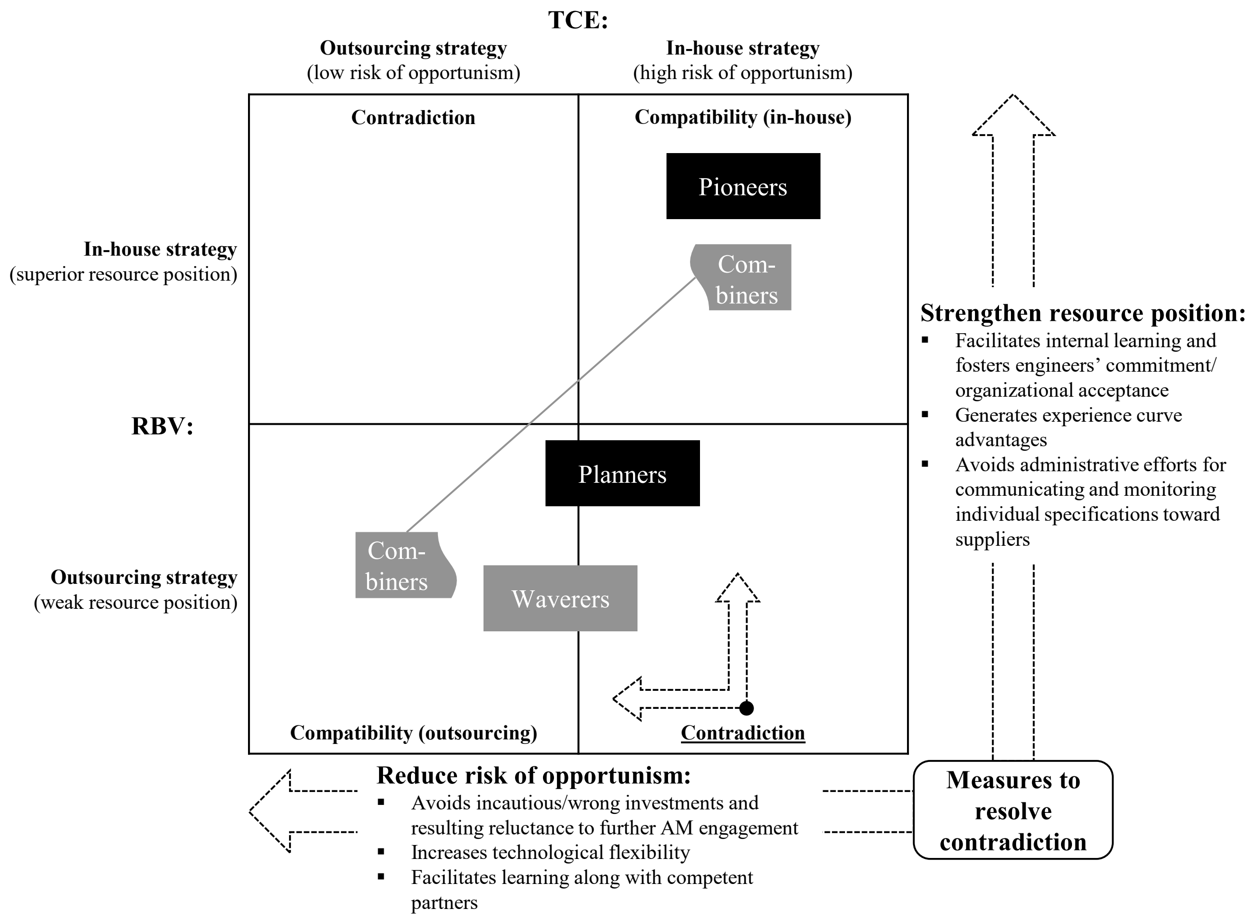


Figure 6-4: Alternative strategies for AM implementation.

## 6.6 Managerial insights

As a direct outcome of our theoretical contribution, this study provides real-world insights for managers confronted with make-or-buy decisions related to industrial AM. We discuss these insights and reflect them in the broader innovation literature.

From the above, we found that strengthening a manufacturing firm's resource position with in-house investments, in light of the high risk of opportunism, is a broadly applied strategy for emerging AM technologies. As depicted in Figure 6-4, strengthening the AM resource position facilitates internal learning. It fosters engineers' participation as well as organizational and cultural acceptance of AM that have been recognized as crucial factors for implementation success of technologies (McDermott & Stock, 1999; Stock & Tatikonda, 2008). Moreover, early in-house investments put manufacturing firms in a suitable position to avoid falling behind competitors and new entrants from the AM domain. The innovation literature contains multiple examples where incumbents have failed to maintain their competitive positions at the shift of manufacturing paradigms (e.g., Ho & Lee, 2015; Vuori & Huy, 2016) and our results indicate that manufacturing firms in AM fear such a loss of position. They aim to generate experience curve advantages to safeguard superior resource positions in the future as suggested by Lieberman and Montgomery (1988). Furthermore – as a classic TCE argument – strengthening the AM resource position avoids administrative efforts for communicating and monitoring individual specifications toward suppliers.

However, our results demonstrate that managers should carefully consider the benefits of this strategy and balance it against the alternative, namely the reduction of the risk of opportunism by building trustful relationships with partners as illustrated in Figure 6-4. AM software and platform providers, AM machine manufacturers, and AM industry experts agreed that copying and counterfeiting can be avoided via existing IT security technologies. For instance, one AM industry expert pointed out, “The concerns are seen as greater than they are. After all, solutions are available on the market.” Manufacturing firms should explore these solutions in more detail to reduce IP concerns as suggested by Kurpjuweit et al. (2021) and Holland et al. (2018).

With a reduced risk of opportunism, we propose that, first, outsourcing avoids overly early investments in specific AM technologies. Hype for novel technologies urges firms to join an “innovation race” (Bakker & Budde, 2012, p. 560), and we find an indication for such behavior in AM. An outsourcing strategy, however, protects firms from restricted returns due to a limited number of applications or a wrong technology choice. Thus, it may prevent first-mover disadvantages (Lieberman & Montgomery, 1988) and a reduction of future innovation activities (Ruef & Markard, 2010) as we observed firms whose initial unsuccessful investment let them shy away from AM entirely and potentially miss actual applications. In this vein, one AM industry expert commented, “Several firms, especially the smaller ones with financial constraints, want to get rid of their purchased AM machines because they simply realize, ‘I have no use for it.’ […] it can happen that the machine just stands still or is only used for gimmicks.”

Second, our findings show that outsourcing provides technological flexibility and, thus, allows manufacturing firms to explore and leverage the multitude of technological options of AM (Folta, 1998).

Third, outsourcing brings the opportunity to learn alongside powerful partners. The innovation literature stresses the benefits of open innovation (Chesbrough, 2003). In a similar vein, when manufacturing firms collaborate more to assess the potential of industrial AM, their chances of identifying suitable business cases are likely to increase (Chaudhuri et al., 2019). Several interviewees from the AM domain supported this argument. One AM service bureau, for example, shared the advice, “Do not buy a machine. Develop applications with partners who know the technology. And once you have understood the technology and realized that it makes sense for you, then you can start buying machines.” In a similar vein, Conner et al. (2014) point out that by gaining knowledge, firms can better estimate if AM constitutes a competitive advantage and make informed decisions.

## 6.7 Concluding remarks

Additive manufacturing rests on digital traits, which the literature expects to ease outsourcing of the AM process. In contrast, we observed that the current state of the AM industry holds various value-creating governance structures for manufacturing firms, ranging from hierarchy- to market-based structures. To develop a deep understanding of the causal processes involved in manufacturing firms’ industrial AM make-or-buy decisions, we used a multiple-case study design. In addition, we gained extensive industrial AM domain knowledge from AM-specific actors.

We identified four AM make-or-buy decision profiles of manufacturing firms characterizing the current variety of governance choices and developed a framework that allows us to explain the rationales of why each of the four profiles emerges. Furthermore, by following an MRT approach, we showed how the empirical context of industrial AM modifies arguments that can be explained following TCE and the RBV. Finally, our study identifies the AM implementation process as a setting in which both theories provide contradicting guidance as to the governance choice. We discussed the advantages and risks of alternative governance structures and raised awareness for an AM market entry with competent partners and cautious implementation of in-house AM.

### 6.7.1 Limitations and future research

Resulting from our methodological choice, our findings are based on insights shared by individual interviewees. We presented viewpoints from manufacturing firms and actors from the AM domain to ensure a coherent overview but included only a limited number of SMEs. We observed that many manufacturing SMEs have not implemented AM yet, hence our findings cannot entirely reflect their specific perspectives. With the increasing prevalence of AM, investigating more SMEs will be a valuable next step, enabling the identification of more differentiated rationales. Furthermore, we built our observations on the retrospective views of interviewees and we cannot rule out that they may be overshadowed by a posteriori insights. A longitudinal case study approach would be beneficial in this regard to focus on the dynamics of the make-or-buy decision profiles and the rationales.

Considering our theoretical lens, we decided to focus on the two polar governance structures, market versus hierarchy. Thus, our study sets the ground for investigating hybrid forms (e.g., alliances, joint ventures, and acquisitions) for industrial AM. This creates an opportunity to extend the derived framework of rationales. TCE and the RBV will likely continue to be a suitable theoretical lens, but future work should also consider if other theories can pinpoint additional nuances in manufacturing firms' decision-making behavior.

When selecting the context of our study, we purposefully chose industrial AM with high-quality requirements and extensive approval procedures. Hence, our findings may lack generalizability to the implementation of AM in industries that do not share these characteristics. Elaborating and testing our propositions in different AM contexts, for instance, in the less regulated consumer industry, is a logical next step.

### 6.7.2 Outlook for emerging digital manufacturing technologies

Albeit from the industrial AM context, we believe that our findings are not limited to AM but are relevant for manufacturing firms implementing technologies with similar characteristics. AM has been coined as a set of inherently digital and emerging manufacturing technologies. The digital traits increase manufacturing firms' IP concerns and drive them to reevaluate their core competencies. The emerging traits, again, increase IP concerns, encourage firms to make risky in-house investments, urge them to learn, and require them to cautiously manage dependency in outsourcing relationships. On an aggregated level, our findings indicate that these rationales may drive firms toward in-house governance for such a setting. The literature suggests that as a nascent market matures, advantages of in-house production are likely to decrease and vertically specialized firms may prevail (Jacobides & Winter, 2005; Malerba et al., 2008; Schilling, 2000).

However, it is not yet clear how digitalization impacts governance decisions in mature digital manufacturing industries. For instance, the more mature and highly digitized semiconductor industry still faces similar IP concerns like the AM industry, including copying and counterfeiting (Gupta et al., 2020). Extensive digital design and data exchange render the digital supply chain more vulnerable than the physical one. A second persisting question is if the digital traits will continue to cause a reevaluation of core competencies and require vertically integrated firms with interwoven expertise in the digital and physical domain. In the case of AM, Ben-Ner and Siemsen (2017) and Massimino et al. (2018) expect valuable and rare digital design resources to become fully decoupled from the physical manufacturing process. Revisiting the more mature semiconductor industry, again, such a decoupling has initiated the evolution of "fabless" actors with digital capabilities and extensive manufacturing outsourcing practices (Monteverde, 1995). Despite this, a large variety of contractual arrangements characterizes the mature semiconductor industry (Mönch et al., 2018) demonstrating that specialized and integrated firms can purposefully coexist (Kapoor, 2013). For AM, such a decoupling will require technological advances that facilitate a truly robust, automated, and flexible physical production process accepting any designs as an input. These observations from industrial AM may provide a basis for extending knowledge on the impact of digitalization on make-or-buy decisions in general.

## Appendix A: Information about the cases and actors from the industrial AM domain

Table A6-5: Information about the cases.

| Manufacturing firm | Case | Product/ service | 2020 annual revenue (millions) | Number of employees | Location of the firm | Interview type | Job position of interviewee |
|---|---|---|---|---|---|---|---|
| End-product manufacturers | E1 | Machinery and equipment | $ 1,000–5,000 | 10,001–20,000 | Germany | Face-to-face[b] | Innovation Manager, Doctoral Candidate[c] |
| | E2 | Industrial conglomerate | > $ 20,000 | >100,000 | Germany | Face-to-face[b] | Head of AM |
| | E3 | Motor vehicles | n/a | n/a | Switzerland | Phone | Head of Technical Development |
| | E4 | Materials handling equipment | $ 1,000–5,000 | 501–5,000 | Germany | Face-to-face | Director Digital Transformation |
| Component manufacturers | C1 | Basic metal | $ 1,000–5,000 | 5,001–10,000 | Germany | Face-to-face[b] | Head of Operational Excellence |
| | C2 | Motor vehicle components | $ 10–20 | 51–500[a] | Germany | Face-to-face[b] | Senior Manager |
| | C3 | Rail transportation equipment | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | Vice President Spare Part Services |
| | C4 | Rail transportation equipment | $ 5,000–20,000 | 20,001–50,000 | France | Video | Chief Technology Officer |
| | C5 | Machinery and equipment | $ 100–500 | 501–5,000 | Germany | Phone | Head Quality Management & Compliance |
| | C6 | Motor vehicle components | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | Head of Additive Technologies |
| | C7 | Machinery and equipment | $ 100–500 | 501–5,000 | Germany | Phone | Development and Technical Testing |
| | C8 | Aerospace equipment | $ 20–100 | 51–500[a] | Germany | Phone | Vice President Business Development |

[a]SME.
[b]Two interviewers present.
[c]Two interviewees present.

Table A6-6: Information about the actors from the industrial AM domain.

| AM-specific actor | Firm | Product/service | 2020 annual revenue (millions) | Number of employees | Location of the firm | Interview type | Job position of interviewee |
|---|---|---|---|---|---|---|---|
| AM service bureaus | S1 | Polymer and metal applications | $ 10–20 | 51–500[a] | Germany | Face-to-face | Key Account Manager |
| | S2 | Metal applications | $ 1–10 | 1–50[a] | Germany | Face-to-face | Managing Partner |
| | S3 | Polymer and metal applications | $ 20–100 | 51–500[a] | Germany | Phone | Head of Marketing & Business Development |
| | S4 | Mobile AM micro-factory | n/a | 1–50[a] | Norway | Video[b] | AM Expert[c] |
| AM machine manufacturers | P1 | AM machines for metals | $ 20–100 | 1–50[a] | Germany | Face-to-face[b] | Sales Engineer[c] |
| | P2 | AM machines for polymers | $ 500–1,000 | 501–5,000 | Germany | Face-to-face | Technical Consultant |
| | P3 | AM machines for metal and polymers | $ 100–500 | 501–5,000 | Germany | Face-to-face | Business Development Manager |
| | P4 | AM machines for metals | $ 20–100 | 51–500 | Germany | Phone | Director Business Development |
| AM material supplier | M1 | Specialty chemicals | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | Head of AM |
| AM software and platform providers | SP1 | Software for AM processes | n/a | 1–50[a] | Germany | Phone | Managing Director |
| | SP2 | Software for AM design automation | n/a | 1–50[a] | Germany | Face-to-face | Managing Director |
| | SP3 | Platform for matching orders and AM service bureaus | $ 1–10 | 1–50[a] | The Netherlands | Video | Chief Operating Officer |
| AM industry experts | I1 | Established AM firm network | Non-profit organization | 1–50 | Germany | Face-to-face[b] | AM Expert[c] |
| | I2 | Consulting firm for AM implementation | n/a | 1–50[a] | Germany | Phone | Managing Partner |

[a]SME.
[b]Two interviewers present.
[c]Internal data provided.

## Appendix B: Semi-structured interview protocol for manufacturing firms (selection for this study)

1. *Background information*
   a. Interviewee information (name, years in the firm, professional and educational background)
   b. Interviewee's relation to AM (job description, responsibilities, connection to AM)
   c. Firm information (firm name, years in existence, size, number and distribution of firm locations, key products and services)
   d. Traditional supply chain (major suppliers and customers, outsourcing experience)
2. *Firm's state of AM implementation*
   a. Start of AM activities (reasons for AM involvement, timeline, first activities, first applications, partners)
   b. AM status (developed structures and know-how in the organization, collaborations)
   c. Current AM supply chain (AM applications, specific AM suppliers and customers)
   d. Assessment of AM (maturity for firm's AM applications, outlook on expectations for AM in 10 years)
3. *AM make-or-buy decision*
   a. How concrete are your firm's ideas regarding the implementation of AM? How have you/will you implement AM in your organization?
   b. Do you expect a change in your vertical integration?
   c. Which competencies are central for you? Would these competencies remain within your firm in an AM supply chain?
   d. Which new competencies do you expect your firm to build for AM?
   e. Do you see a need for new partners in AM supply chains?
   f. Are the business models of existing partners changing?
4. *Wrap up*
   c. What are the critical milestones for future AM development?
   d. If you could change one existing condition/limitation, what would that be?

# 7 Study B.2: Supply chain design for industrial additive manufacturing[28]



| | |
|---|---|
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**Abstract**

**Purpose** – This study extends and refines the current knowledge on emerging supply chain designs (SCDs) for industrial additive manufacturing (AM) and manufacturing firms' rationales in selecting them.

**Design/methodology/approach** – Following an exploratory research design, a multiple-case study is conducted in the context of industrial AM. It focuses on two key dimensions of SCD, the geographic dispersion and governance structure. Four cohesive AM SCD configurations are characterized and form the basis for exploring the rationales for the SCD decision of manufacturing firms.

**Findings** – The findings indicate that manufacturing firms' SCD for industrial AM depends on the trade-off between economies of scale in a centralized setting and the market potential from customer proximity realized by decentral AM. Furthermore, the control of suppliers and the reevaluation of manufacturing firms' core competencies guide the governance choice. Many of the identified rationales currently drive manufacturing firms toward in-house AM at a centralized location or distributed AM in a secure, firm-owned network.

**Practical implications** – The arguments for the AM SCD choices are illustrated. They provide guidance for managers of manufacturing firms when implementing industrial AM.

**Originality/value** – The study reveals and enhances the understanding of why the extant academic expectation of decentralized and outsourced AM is not sufficiently reflected in current industry practice. Thereby, the study provides a basis for elaborative decision-support research on AM SCDs.



**Keywords:** Additive manufacturing, 3D printing, Distributed manufacturing, Supply chain design, Supply chain governance, Case study research

**Paper type:** Research paper


## 7.1 Introduction

Industrial additive manufacturing (AM) technologies are expected to disrupt traditional manufacturing and supply chains (SCs) (Olsen & Tomlin, 2020). The entire AM sector has seen an average annual growth of 25.7% over the past ten years (2011–2020) (Wohlers Associates, 2021b), providing a glimpse of what may still come. As manufacturing firms have started to use AM for industrial production, they have implicitly or explicitly decided on a supply chain design (SCD) for their AM operations.

The operations and supply chain management (OSCM) literature observes that a value-creating SCD must adapt to its context. This understanding has been firmed since Fisher (1997) raised the

[28] The manuscript of the article has been slightly modified to ensure consistent format and style throughout this thesis. Note that the pronoun "we" is used in this chapter to refer to the authors of the article.

question, “What is the right supply chain for your product?” for consumer products. Turbulences that require SC adaptation can emanate from various sources, including the demand side, supply side, political and financial factors, and novel technologies such as industrial AM (Christopher & Holweg, 2011). We consider SCs to be structures that allow manufacturing firms to implement their competitive strategies. There is a direct link between SCs and business strategy to ensure firm competitiveness (Hofmann, 2010). SCs that align with competitive strategies enable firms to create value (Miller, 1986). Our study starts from this premise and addresses how industrial AM impacts the SCD choice. We understand manufacturing firms – component and end-product manufacturers – as the dominant actors in SCs who determine the SCD to a large extent.

The spectrum of alternative SCDs for industrial AM is broad, and it is far from obvious whether one approach is better than others: General Electric has used AM in serial production since 2015, famously producing its LEAP aircraft engine’s fuel nozzle tip additively at a central manufacturing plant in Auburn, Alabama (GE Additive, 2018). Maersk started installing polymer 3D printers on board sea vessels. Instead of storing spare parts, a part is additively manufactured on demand from its digital specification at the remote location (Krassenstein, 2014). BMW opened its central Additive Manufacturing Campus and distributed more than 50 AM machines inside its worldwide production network (BMW Group, 2020). Bugatti, a French high-end automotive manufacturer, tightly cooperates with an AM service bureau and purchases additively manufactured titanium exhaust finishers for serial production (Metal AM, 2021).

These examples demonstrate that manufacturing firms select different SCDs ranging from centralized (e.g., General Electric) to decentralized AM at the point of demand (e.g., Maersk) and from in-house production (e.g., BMW) to outsourcing to specialists from the AM domain (e.g., Bugatti). However, the current understanding of AM’s impact on SCD choices is still vague. The growing OSCM literature on AM strengthens the belief that AM will enable distributed manufacturing and, thus, lead to shorter, decentral, and simplified SCs in the long term (Kumar et al., 2020; Srai et al., 2020). Traditional decision-making regarding manufacturing locations is driven by arguments on economies of scale, hence, entailing for manufacturing locations to achieve a specific minimum level of scale. However, location-independent AM machines can be flexibly placed anywhere in the downstream SC, close to or even at the point of demand (Ghobadian et al., 2020; Olsen & Tomlin, 2020). Furthermore, the literature expects AM to foster outsourcing of manufacturing activities since the technologies rely on easily transferable digital design files and general-purpose equipment (Berman, 2012; Hedenstierna et al., 2019). Manufacturing firms are envisioned to take short-term, flexible outsourcing decisions, potentially working with “pools of local (generalized) service providers” (Holmström et al., 2016, p. 5) to benefit from the combination of outsourced and decentralized AM.

These literature-based visions of decentral AM SCs and extensive outsourcing do not reflect the variety of SCDs in practice, and little is known about the rationales for specific AM SCDs yet. This study aims to develop a perspective on cohesive AM SCD configurations in the industrial AM context and explore the rationales of manufacturing firms. We focus on two dimensions, the geographic dispersion (central versus decentral) and governance structure (in-house versus outsourcing). We address this objective in two exploratory research questions (RQs):

**RQ1:** *How* do manufacturing firms design their SCs for industrial AM on the spectrum of geographic dispersion and governance structure?

**RQ2:** *Why* do manufacturing firms opt for these specific AM SCDs? Or, more formally, what are the rationales behind the SCD choices?

We chose a case study approach that lends itself to tackling *how* and *why* questions (Eisenhardt, 1989; Yin, 2014). More specifically, we collected insights from traditional and AM-specific SC actors on four SCD configurations for industrial AM along the two dimensions of geographic dispersion and governance structure. In a within-case analysis, we characterize what constitutes and sets apart each of the four AM SCD configurations. By analyzing across the four cases, we explore the underlying causal processes of manufacturing firms for selecting these SCDs. We identify 21 rationales related to economies of scale, market potential, control, and core competencies that are constrained by embedding AM in an existing SC context.

Our foremost theoretical contribution is the in-depth understanding of the SCDs that manufacturing firms currently implement for industrial AM. We theorize in the industrial AM context to build domain knowledge on emerging SCDs. With such a nuanced, real-world perspective, we significantly extend and refine the nascent research stream addressing the impact of AM on SCD in the OSCM literature (e.g., Durach et al., 2017b; Verboeket & Krikke, 2019). Our findings indicate that manufacturing firms currently select AM SCDs that differ from the literature-based vision of decentralized, outsourced AM. By analyzing their rationales, we distill why specific configurations provide a fit for manufacturing firms' competitive strategies, suggesting that decentralized, outsourced configurations will likely not become the "one-size-fits-all" SC structure for industrial AM. Moreover, we offer guidance to managers who are currently challenged in how to suitably integrate AM into their SCs.

The structure of this paper is as follows. Section 7.2 introduces the literature background and Section 7.3 explains our case study methodology. Section 7.4 characterizes the AM SCD configurations individually (within-case analysis) and explores the rationales across the configurations (cross-case analysis). Section 7.5 discusses how our findings contribute to current knowledge on AM SCD and provide managerial insights. Section 7.6 presents our conclusions.

## 7.2 Background

### 7.2.1 Context of industrial additive manufacturing supply chains

AM technologies are at an emerging stage (Rong et al., 2018) and are therefore recognized as technologies that have not demonstrated their full potential to outperform traditional manufacturing technologies yet. The technologies are fundamentally different from traditional subtractive manufacturing in that they create parts by adding material layer upon layer. This brings a revolution to the way parts are designed, for example, lightweight structures for aerospace parts that enable more efficient flight operations (Gibson et al., 2015). Moreover, AM facilitates manufacturing directly from the digital design file without product-dependent setup and tooling (Holmström et al., 2016; Olsen & Tomlin, 2020). With such a one-step process, AM makes it possible to create rapidly available parts (Khajavi et al., 2014).

AM also has a famous consumer side, commonly referred to as polymer 3D printing (Thomas-Seale et al., 2018). Consumer 3D printing creates new opportunities for customization ("personalized manufacturing") and customer co-creation (Bogers et al., 2016; Christopher & Ryals, 2014). Here, we focus on industrial AM – the professional application of AM in the business-to-business context where customization to the single customer is less needed, and co-creation activities may instead emerge with suppliers or as "self-services" of industrial customers (Rogers et al., 2016). Industrial AM technologies comprise AM machines for metal AM and high-quality polymer parts. We study industrial AM SCDs, which implies that manufacturing firms have already made a technology choice. Each AM technology has specific technological and economic implications for the SCD. In particular, metal AM is more investment-intensive than polymer AM (Wohlers Associates, 2021b). It is also more complex to handle and requires more labor- and equipment-intensive pre- and post-processing (Knofius et al., 2021). Overall, typical applications for industrial AM are new parts and spare parts, tools, jigs and fixtures, and prototypes (Fontana et al., 2019; Gartner, 2019).

Since the late 1980s, industrial AM technologies and materials have developed great steps. Manufacturing firms from the aerospace and automotive industry were the first to take advantage of the revolutionary design opportunities and the benefits of rapidly available prototypes (Wohlers Associates, 2021b). In addition, the transportation and machinery and equipment industries are among the sectors that have started to gain AM expertise early, for example, for manufacturing obsolete spare parts and internal applications like tools and fixtures (EY, 2019). Our study reflects these pioneering industries where industrial AM creates value and manufacturing firms have started to integrate the technologies into their SCs.

Today, the AM market qualifies as a nascent one, and the same is true for AM SCs. Santos and Eisenhardt (2009, p. 644) characterize nascent markets as "unstructured settings with extreme ambiguity." Positions and relations of new suppliers from the AM domain and traditional SC actors are not fully established because firms are at an early stage of formation: Analog to the traditional role of suppliers, specialized AM suppliers have started to provide AM machines, AM materials, and software and platform solutions for the physical and digital manufacturing infrastructure (Chekurov et al., 2018; Verboeket & Krikke, 2019). Consulting firms and AM industry networks possess extensive market knowledge and share expertise with their customers and partners (Bugdahn et al., 2019). From these new AM-specific actors, AM service bureaus stand out as the predestined outsourcing partners for AM. As contract manufacturers for industrial AM, they offer manufacturing services, including pre- and post-processing and further auxiliary services (Chaudhuri et al., 2019; Rogers et al., 2016). Figure 7-1 structures how these new suppliers from the AM domain approach traditional manufacturing firms that maintain business-to-business relationships with their industrial customers. Together, the outlined actors compose the industrial AM SC. Their perspectives are all considered for our case study approach of exploring AM SCD configurations with a focus on component and end-product manufacturers based on their focal position.

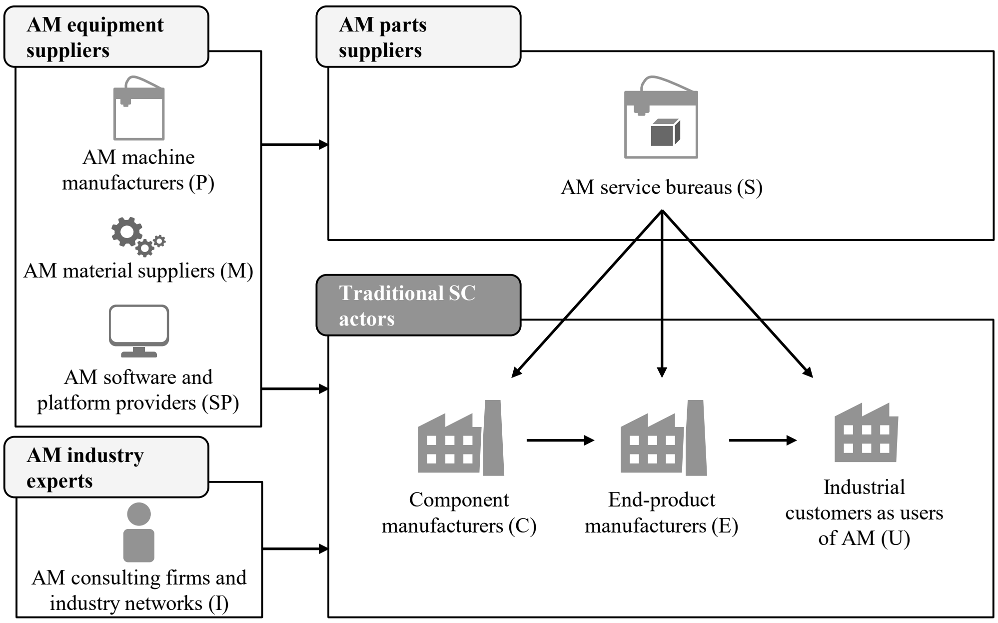


Figure 7-1: Actors of industrial AM SCs.

### 7.2.2 Supply chain design decision

SCD decisions include the number and location of production facilities, each facility's capacity, and sourcing and distribution policies (Beamon, 1998; Kouvelis et al., 2006). SCD research has traditionally focused on designing consumer SCs that are in harmony with specific product types and/or demand characteristics (e.g., Christopher, 2000; Fisher, 1997; Vonderembse et al., 2006); see Seuring (2009) for a broader introduction to the literature contributing to the SCD decision with an emphasis on consumer demand. In contrast, we focus on industrial SCs with manufacturing firms in a focal position from which they maintain relationships with upstream suppliers and manufacture products for industrial customers (Choi & Krause, 2006). Fine (2000) coins the term "dominant producer" for what we consider a focal firm in the SC. He defines the SCD choice as "choosing what capabilities along the value chain to invest in and develop internally and which to allocate for development by suppliers" (Fine, 2000, p. 213). This definition narrows the SCD choice to how a focal manufacturing firm sets its boundaries to determine the *governance structure* of a SC. In addition to the governance structure, we focus on the *geographic dispersion* as a second fundamental dimension of the SCD choice, in line with, for instance, Shi and Gregory (1998) and Stock et al. (2000). The resulting model simplifies SCD to two dimensions and allows us to delineate essential rationales behind AM SCD choices. In a nutshell, geographic dispersion refers to the extent to which the entities of a SC span across geographic regions (Handley & Benton, 2013). We want to capture whether manufacturing firms implement AM concentrated at a central location in the SC, or alternatively, if they opt to manufacture a part decentrally and potentially close to its demand. The governance structure addresses the vertical scope of a SC and, with that, establishes the difference between vertically integrated and outsourced SCs (Rudberg & Olhager, 2003; Tsay et al., 2018). Manufacturing firms must decide whether to operate AM machines themselves in-house or outsource these activities to an AM service bureau.

We apply a configurational approach, following Miller (1986), to investigate industrial AM SCDs. Traditionally, configurations of organizations are characterized by a set of dimensions that appear in coherent patterns. Here, a configuration refers to a SCD that is commonly and consistently selected across multiple manufacturing firms and clearly distinguishable from others. The configurational approach aims to identify and establish such profiles. It expects organizations to adapt their structures to create a *fit* to changes in their external environment and to maintain internal consistency (Miller, 1992). This study postulates that AM is a novel source of misfit for manufacturing firms' traditional SCD (i.e., their structure). Manufacturing firms are forced to adapt their SCD reactively to (re-)create an external fit to the opportunities and constraints arising with AM implementation. Internal fit requires firms to align their AM SCD to their competitive strategies following Miller (1986; 1992). It is a fundamental hypothesis to our study that the AM SCDs implemented by manufacturing firms are aimed at creating such internal and external consistency.

### 7.2.3 Expectation of decentral, outsourced additive manufacturing supply chain design

The OSCM literature recognizes the need to redesign traditional SCs to accommodate industrial AM (Holmström & Partanen, 2014; Luomaranta & Martinsuo, 2020). First studies have specifically addressed the geographic dispersion or the governance structure of AM SCs: Holmström et al. (2010), Liu et al. (2014), and Khajavi et al. (2018; 2014) compare total SC costs of central versus decentral AM SCs for spare parts in the aerospace industry. Pérès and Noyes (2006), Westerweel et al. (2021), and den Boer et al. (2020) investigate the benefits of decentralized spare parts SCs for AM at remote or isolated locations (e.g., military/humanitarian missions and space stations). For the governance structure of AM SCs, Hedenstierna et al. (2019) propose a bidirectional partial outsourcing mechanism for flexibly trading general-purpose AM capacities between alternating partners. Meyer et al. (2021) analyze how AM impacts strategic sourcing decisions. Moreover, Friedrich et al. (2022b) detail how the specifics of AM, the technologies' digital and emerging traits, affect manufacturing firms in their AM make-or-buy decisions. In addition, Chaudhuri et al. (2021) provide domain-specific insights into AM make-or-buy decisions of hospitals, and Hohn and Durach (2021) study AM's effect on SC governance in the apparel industry.

Beyond these specific insights, the broader OSCM literature provides arguments that have implications for the AM SCD decision. We identify four factors that support that decentralized, outsourced SCDs are likely outcomes when integrating AM: *technology*, *physical infrastructure*, *digital infrastructure*, and *competencies* (see Figure 7-2).

| AM factor | Description | Representative references |
|---|---|---|
| Technology | **General-purpose AM machines** with **no product-dependent setup** and **tooling** | Holmström and Partanen (2014); Holmström et al. (2016) |
| | **No irreversible investment** in part- or customer-specific machines | Scott and Harrison (2015) |
| | **Flexible outsourcing** and **pooling** of orders from multiple customers since different designs can be manufactured in one job | Rogers et al. (2016); Durach et al. (2017b) |
| | Economic manufacturing of **small volumes** | Berman (2012); Kumar et al. (2020); Luomaranta and Martinsuo (2020); Olsen and Tomlin (2020) |
| | **Minor relevance** of **economies of scale**; static economies of scale occur for the capacity utilization of the build volume of the AM machine | Baumers and Holweg (2019) |
| Physical infrastructure | **Location independence** from other manufacturing locations (e.g., for tooling) | Verboeket and Krikke (2019) |
| | AM machine as a **compact production unit**; **limited space requirements** and **transportability** | Kumar et al. (2020) |
| | **Basic raw materials**; easily supplied via **bulk transportation** | Zijm et al. (2019); Verboeket and Krikke (2019) |
| | Labor-intensive **pre- and post-processing** | Knofius et al. (2021) |
| | Expected future increase in the **automation of AM machines** including pre- and post-processing; reduction in labor intensity | Khajavi et al. (2014); Mellor et al. (2014) |
| | Overall **reduction** of the **complexity** of the physical SC based on AM; **fewer suppliers**, **stages**, and **interactions** | Durach et al. (2017b); Luomaranta and Martinsuo (2020) |
| Digital infrastructure | **Ease of sharing**, **modifying**, and **reusing** digital files | Berman (2012); Ruffo et al. (2007) |
| | **Low transaction costs** for transferring the unambiguous digital product specification to an outsourcing partner | Baumers and Holweg (2019); Hedenstierna et al. (2019) |
| | Required **robust information and communication technology** for data transmission | Holmström et al. (2010); Kurpjuweit et al. (2021) |
| | Concerns about the distribution of **intellectual property (IP)** | Chekurov et al. (2018); Massimino et al. (2018) |
| Competencies | **Valuable AM design** and **software skills** | Rylands et al. (2016) |
| | **No specific** and **easy-to-acquire AM production skills**; considered to be available on the labor market | Ben-Ner and Siemsen (2017); Chekurov et al. (2018) |
| | **Exchangeability** of **outsourcing partners** | Holmström et al. (2016); Zijm et al. (2019) |

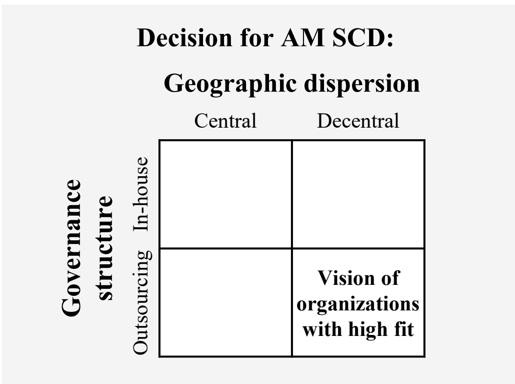


Figure 7-2: Literature findings on AM SCD.

The technological features of AM are attractive for outsourcing and enable decentralized operations because no tooling and setup are required, and economies of scale are of minor relevance. The requirements for the physical infrastructure in AM SCs are low, suggesting that decentral operations are more likely for AM than for traditional manufacturing technologies. However, industrial AM applications currently require pre- and post-processing, which complicates decentral operations. Previous research emphasizes that the simplicity of transferring and sharing the digitally available AM designs fosters outsourcing, but intellectual property (IP) concerns emerge as a practical challenge related to secure digital infrastructure. Likewise, the skills in the digital domain (i.e., AM design and software skills) are the new source of competitive advantage in AM, while production skills are considered to be relatively easy to acquire and available on the labor market. Hence, existing work argues that outsourcing is possible and partners can be flexibly exchanged when necessary, as manufacturing additively does not depend on specific skills. In summary, the identified arguments for decentralized, outsourced SCDs for industrial AM entail that such SCDs will create a high fit for manufacturing firms (see Figure 7-2).

## 7.3 Methodology

### 7.3.1 Research design and context

We opted for a multiple-case study research design, following Eisenhardt (1989). Driven by our research questions, we defined SCD configurations for industrial AM as our *units of analysis*. We selected four cases based on our pre-defined scope of geographic dispersion and governance structure (see Figure 7-3). By focusing on the four polar fields of the matrix, our case selection followed a theoretical replication logic of choosing extreme cases where we expect contrasting patterns of AM SCDs to be observable (Voss et al., 2002). Applying such a replication design for case selection increases the external validity of our multiple-case study (Yin, 2014). Since we embedded our case study in the industrial AM context, we found suitable AM SCs in industries that have demonstrated their positions as early adopters of industrial AM (see Section 7.2.1), including the aerospace industry, rail and automotive industry, and low-volume machinery and equipment industry. SCs in these industries traditionally differ in their governance structure and geographic dispersion (Christensen, 2011; Tretheway & Markhvida, 2014), which fostered our expectation of gaining insights into a great variety of industrial AM implementations in SCs and emerging AM SCDs.

Data cannot be collected directly from the SCs (Durach et al., 2017a); hence, our *units of data collection* are the firms along the SCs in these industries (see Figure 7-3). We selected firms that already have experience with industrial AM and actively design or are involved in such SCs as our data collection units. To identify suitable firms, we conducted web searches (e.g., via AM news websites and reports), visited AM industry events, and contacted an internationally recognized AM industry network. We initially targeted end-product and component manufacturers as these are the focal firms that take the key SCD decisions for their products. In addition, we also included industrial customers as users of AM in our sample to reflect their perceptions. Furthermore, we opted to involve AM service bureaus as the predestined outsourcing partners and AM-specific suppliers for their market knowledge and understanding of their customers' SCs across the entire range of industrial AM applications.

When our sample contained 28 firms, we noticed that we still lacked a comprehensive understanding of the decentralized configurations (case 2 and case 4). Therefore, we purposefully followed up on firms' recommendations with a snowballing approach, as suggested by Small (2009). We incorporated the perspectives of five additional firms known for their involvement in decentral AM SCs (i.e., use cases in military settings and rail maintenance).

Among the final sample of 33 firms, 19 firms are traditional SC actors, and 14 firms come from the AM domain. The sub-sample of traditional SC actors consists of 12 manufacturing firms from the automotive (3), rail (2), aerospace (1), and low-volume machinery and equipment (6) industries, and of seven industrial customers, mainly from the transportation industry (e.g., train operators and logistics service providers). Some of them have experience with multiple SCDs for different AM applications, see Figure 7-3. All the firms in the sample have their headquarters in Western Europe with a focus on Germany, as the country has a strong competitive position in the (metal) AM industry (Wohlers Associates, 2021b), see Appendix A for details. Only two manufacturing firms are classified as small and medium-sized enterprises (SMEs). As faster diffusion of innovations in larger firms is a well-known phenomenon (van de Vrande et al., 2009) and has been observed for AM (Marzi et al., 2018), our focus reflects the current activities in industrial AM well. Thus, the composition of our sample and, consequently, our analysis mostly reflects perspectives that we collected from the aforementioned industries from large, Western European manufacturing firms that entered the AM market early (see Appendix A). We expect that such manufacturing firms can leverage our findings to advance in the implementation of industrial AM in their SCs.

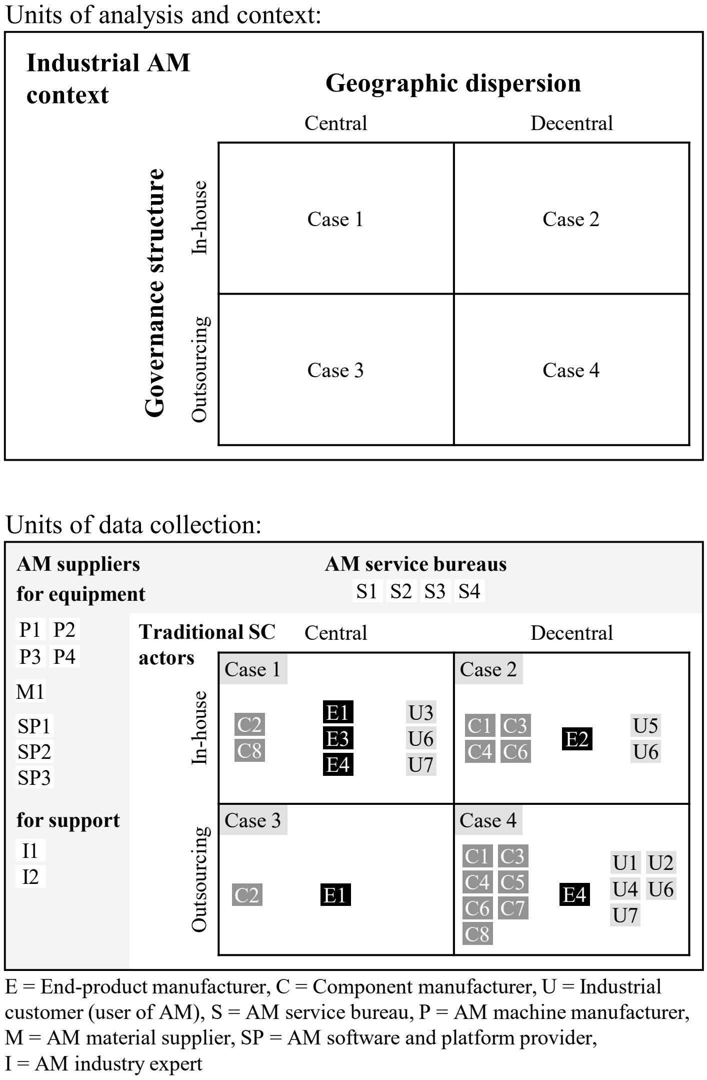


Figure 7-3: Research design.

## 7.3.2 Data collection

We collected data about the AM SCD configurations via semi-structured interviews with individuals from the firms between February 2019 and April 2020. We went back and forth between collecting and analyzing our data, thus, iteratively adjusting our data collection as our data structure emerged (see Eisenhardt, 1989). Note that industrial AM applications are still scarce, so the pool of knowledgeable firms is limited. Furthermore, we observed that there is typically a very limited number of decision-makers within firms when it comes to AM. We conducted one in-depth interview per firm with one or two interviewees present. Our interviewees are directly involved in AM and hold management positions (see Appendix A).

We developed an interview protocol and standardized the data collection process to increase the replicability of results and, thereby, our study's reliability (Gibbert et al., 2008). We structured the interview protocol to gain insights into implemented AM SCDs and involved rationales for selecting these. It was designed from the perspective of manufacturing firms and adapted to the supplier/customer perspective of other interviewees accordingly (see Appendix B). We contacted candidates via e-mail and/or phone and sent a letter of introduction outlining the purpose of our study, the general topic, and organizational details. Interviews lasted between 30 and 90 minutes (on average, 59 minutes). Eighteen face-to-face interviews took place at the firm's location and 15 interviews via video or phone. To increase reliability, two authors jointly conducted nine interviews. We triangulated the responses of interviewees with supplemental data from publicly available documents (firms' websites and press releases) and internal documents provided by some interviewees (see Appendix A) to achieve stronger substantiation and construct validity.

### 7.3.3 Data analysis

We transcribed the recorded interviews and sent them to the interviewees for content verification. The transcripts with supplemental data resulted in 520 single-spaced pages. The data analysis applied open, axial, and selective coding, as suggested by Corbin and Strauss (2015). Coding was conducted using the qualitative data analysis software MAXQDA. To ensure consistency, we intensively discussed codes and resolved conflicts. We first focused on developing a comprehensive understanding of how AM is integrated into each of the four SCD configurations (within-case analysis). The characterization of each configuration emerged from interviews with multiple firms that had insights to share on the specific configuration (see Figure 7-3). Subsequently, we derived a data structure of AM factors and underlying rationales for manufacturing firms' AM SCD choices by analyzing across the configurations (cross-case analysis). Figure 7-5 in Section 7.4.2 serves as an overview to illustrate how our data structure evolved from concepts identified in our coded data, to second-order themes, and aggregated to AM factors following the scheme by Gioia et al. (2013) and Corley and Gioia (2004). To ensure internal validity, we positioned our results within the existing OSCM literature, as outlined in Section 7.2.3. In addition, we presented preliminary findings to interviewees in a one-hour web session in March 2020. Using their feedback, we extended the "chain of evidence" (Yin, 2014, p. 122) between data collection and the retrieved results.

## 7.4 Findings

We first present and build an understanding for the four AM SCD configurations individually to address RQ1, before we explore across the configurations why manufacturing firms opt for specific AM SCDs to target RQ2.

### 7.4.1 Additive manufacturing supply chain design configurations

Figure 7-4 summarizes the characteristics of the four configurations from a focal firm perspective and links them to schematic AM SCDs.

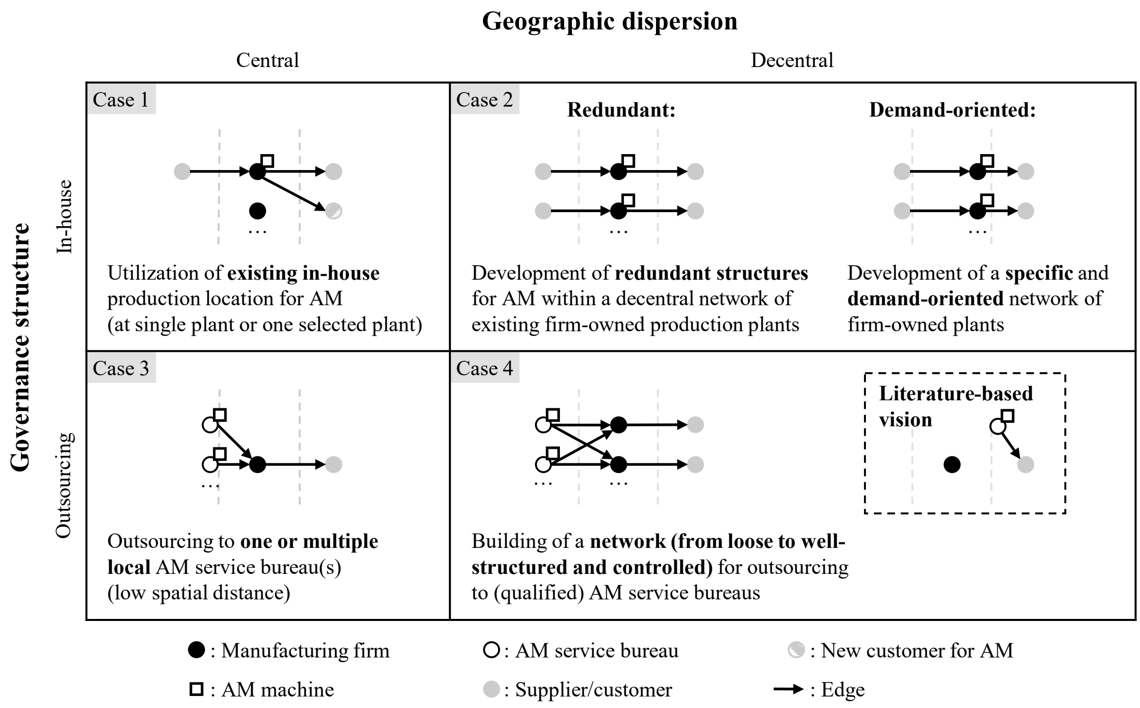


Figure 7-4: Characterization of the four AM SCD configurations.

**Centralized, in-house configuration:** This configuration is dominated by larger manufacturing firms that own AM machines and set up one location for AM. Typically, they select their headquarters for establishing AM competence centers or specialized teams. In addition, we found for this configuration that manufacturing firms vary in their AM implementation stages, from initial to advanced. With senior management's support, initial implementers have only recently installed polymer 3D printers to gain experience. Advanced implementers entered the AM market early to build specific design and production skills in-house. They are in the process of establishing standard routines for AM and applying them to the full spectrum of industrial AM applications, from polymer prototypes to small series of new parts. The centralized positioning of AM in their SC allows these manufacturing firms to exploit their AM expertise and reputation, for example, by establishing an AM third-party business for new industrial customers (see Figure 7-4).

**Decentralized, in-house configuration:** Manufacturing firms that select this configuration standardize their approach toward AM and develop redundant structures for AM among multiple firm-owned locations. Thus, they use existing traditional manufacturing plants to co-locate AM. For example, one multinational conglomerate in our sample builds expertise at the edge of AM technologies by relying on existing manufacturing infrastructure. The interviewee shared, "The influence of AM on location decisions is very limited. We have implemented AM at the locations of traditional manufacturing." In addition, we also found evidence that the decentralized, in-house configuration enables manufacturing firms to create value through their decentral locations. Experienced manufacturing firms that have entered the AM market early develop strategic in-house structures to move AM closer, or ultimately, to the point of demand. For instance, a component manufacturer in the railway sector orchestrates a secure network of AM machines at firm-owned service depots and national subsidiaries. The firm can internally ensure quality while reducing the lead time of spare parts for industrial customers like train operators compared to centralized AM.

**Centralized, outsourced configuration:** This configuration contains manufacturing firms that outsource AM by relying on local AM service bureaus for prototyping and tooling and, therefore, only for internal purposes with comparatively low quality requirements. Such manufacturing firms may remain at an initial AM implementation stage with limited influence of AM on their supplier base. Moreover, this configuration is selected for low-volume applications and test parts before manufacturing firms identify qualified AM service bureaus with a national or international tender process or switch from AM to traditional manufacturing technologies (e.g., for their cost efficiency for higher volumes). We consider the configuration to be centralized due to its proximity to AM service bureaus. It is this proximity that enables fast coordination and simplified collaboration between AM service bureaus and manufacturing firms. For instance, one end-product manufacturer commented, "The local AM service bureau is extremely cheap, extremely fast."

**Decentralized, outsourced configuration:** Outsourcing in decentralized settings differs in the collaboration intensity. Manufacturing firms that have only recently implemented AM outsource the manufacturing process in loose collaboration with one or more AM service bureaus for initial pilot studies. In contrast, advanced AM implementers shift their AM production volume into well-structured and controlled networks of AM service bureaus. They outsource AM to access specialized and rare AM technologies and benefit from AM service bureaus' reliable, high-quality parts. A component manufacturer formulated, "AM service bureaus are audited, selected, […] and then we train our suppliers. So, we do that for AM just like for traditional manufacturing." For these manufacturing firms, outsourcing compensates for in-house capacity shortage and is only used for applications without IP concerns, thus, where no core know-how is involved. So far, the manufacturing firms at both an initial and advanced AM implementation stage do not intend to work with AM service bureaus because of their specific location.

We summarize from analyzing the four configurations individually that strategic decentralization to approach the point of demand occurs currently only within organizations. Manufacturing firms move AM closer or even to the point of demand based on existing in-house structures. Furthermore, we found in-house AM implementation to follow the location decisions made for traditional manufacturing. However, we did not observe in our sample that manufacturing firms outsource industrial AM to leverage the partner's location as expected from literature-based arguments. Instead, outsourcing happens with local partners, loose networks for initial pilots, or the location is a by-product of selecting a partner for quality.

By comparing the AM applications and AM implementation stages of manufacturing firms for the four configurations (see Appendix C), we identified that in-house AM capacities are oftentimes reserved for IP-relevant, demanding applications. This is in particular the case for investment- and know-how-intensive metal AM. Outsourcing is more widespread across various AM applications and is a pronounced strategy for less demanding polymer prototypes without IP concerns. We further observed that manufacturing firms at an advanced AM implementation stage dominate the in-house configurations. In comparison, the outsourced configurations tend to be selected by manufacturing firms at more diverse AM implementation stages.

Industrial customers and AM-specific suppliers provided additional framing to the configurations: Most notably, industrial customers assessed extremely decentralized configurations (e.g., manufacturing firms placing their AM machines directly at the locations of industrial customers) in a rather disillusioned way as "science fiction" and a "belief in miracles." In particular, the combination of decentralized AM and outsourcing was evaluated as being unrealistic. We found that industrial customers rather envision themselves placing their own polymer 3D printers at their decentralized locations for "self-services" of very specific applications (e.g., for spare parts of the warehousing automation or in military settings). Suppliers from the AM-domain mirrored that strategically decentralized configurations to approach the point of demand may only be reasonable choices for very selected spare parts and non-demanding prototypes. Interestingly, AM service bureaus, as the predestined outsourcing partners of manufacturing firms, confirmed that they currently operate centralized manufacturing plants for AM. This suggests that the necessary manufacturing infrastructure and partners, which would enable manufacturing firms to opt for the decentralized, outsourced configuration, may not be sufficiently available yet.

### 7.4.2 Rationales of manufacturing firms

The perspectives collected across the four configurations from manufacturing firms, industrial customers, and AM-specific suppliers enable us to explore and structure the rationales of manufacturing firms for selecting specific AM SCDs. Figure 7-5 visualizes the process of how the data structure for the AM factors and underlying rationales emerged.

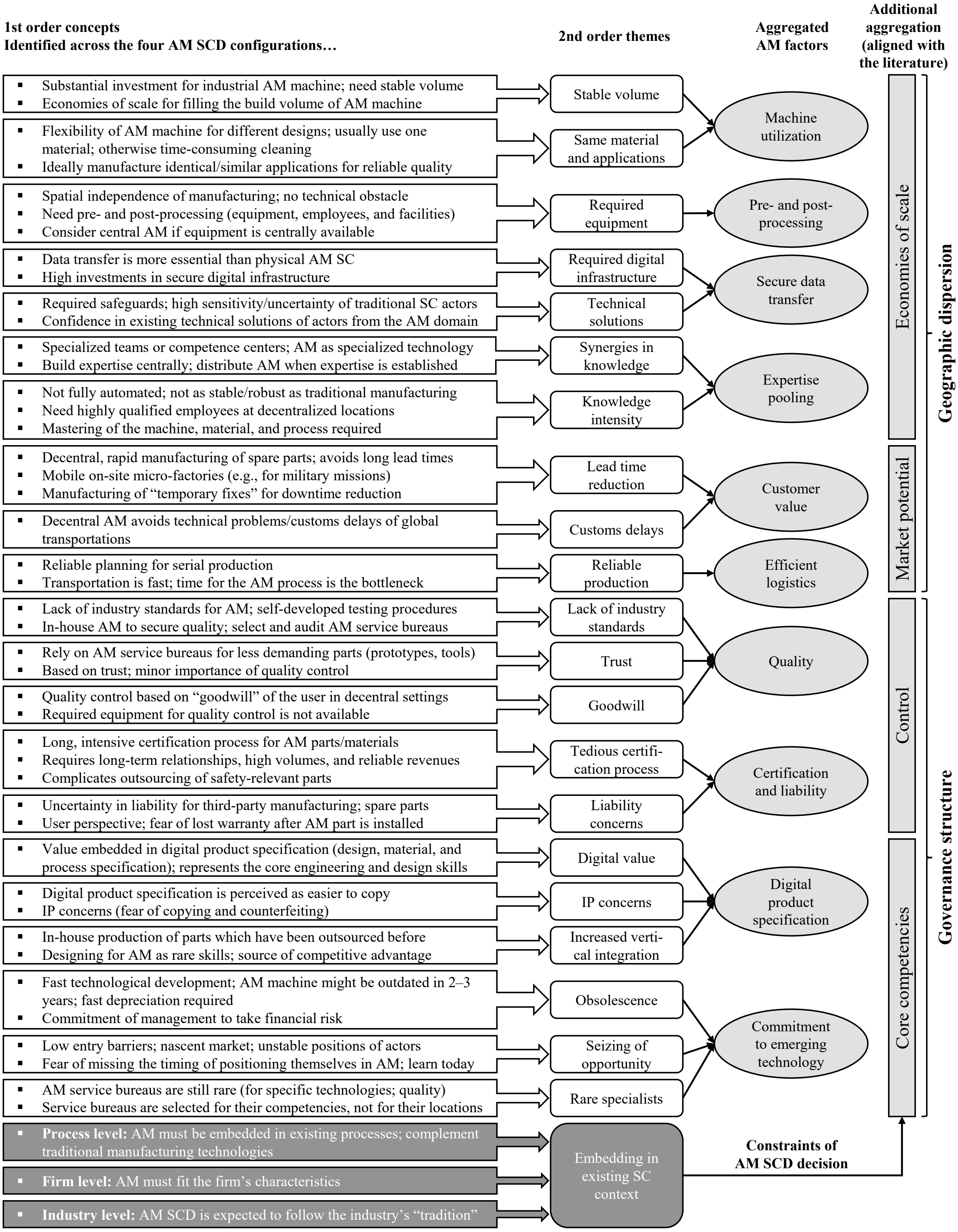


Figure 7-5: Data structure for exploring the rationales.

Figure 7-5 consists of ten AM-specific factors capturing the rationales of manufacturing firms: *machine utilization*, *pre- and post-processing*, *secure data transfer*, *expertise pooling*, *customer value*, *efficient logistics*, *quality*, *certification and liability*, *digital product specification*, and *commitment to emerging technology*. Aligned with extant literature, we aggregated the ten factors to *economies of scale*, *market potential*, *control*, and *core competencies*. The former two relate to the geographic dispersion, the latter two to the governance structure. Moreover, we found that industrial AM SCD decisions must be embedded in the existing SC context. The structure of Figure 7-5 is the basis for the following three subsections presenting our results, and Appendix D provides additional representative quotes underpinning our discussion.

#### 7.4.2.1 Geographic dispersion

**Economies of scale**

Economies of scale are one of the main arguments for centralized operations (Choi & Hong, 2002). Pooled orders create sufficient scales for efficient utilization of resources. We found arguments for economies of scale in the utilization of AM machines, infrastructure for pre- and post-processing and secure data transfer, and pooling of expertise. Industrial AM machines require substantial investment, particularly for metal applications. High **machine utilization** at a stable rate allows manufacturing firms to make the best use of the investment. Interviewees drew attention to the argument that batch planning should respect the build volume of AM machines. We observed across most interviewees that generating sufficient decentral demand to ensure decentral machine utilization substantially impacts manufacturing firms' geographic location decisions. For instance, one end-product manufacturer shared, "When we talk about serial production […] decentral production makes no sense because I lose all economies of scale." This is even more relevant as state-of-the-art AM machines usually handle a single type of material and require cleaning and setup in-between production runs. Furthermore, only similar or ideally identical processes ensure reliable, high-quality parts. These additional constraints currently limit cost-efficient AM operations to a few applications, and most of them require a central location to pool sufficient demand.

Concerning the manufacturing infrastructure, interviewees emphasized that in its present state, AM is far from full automation and mentioned a wide range of tasks for **pre- and post-processing** (e.g., design adjustments, removal of support structures, further traditional manufacturing steps, and surface and heat treatments). These tasks require process knowledge, specific equipment, and are crucial for product quality. An AM industry expert even stated, "I produce a raw part. Nearly no AM component is available that has not been post-processed in a traditional way […]." The more pre- and post-processing is required along with a specific AM application, the more arguments are heard in favor of centralized operations since resources for pre- and post-processing can be pooled across AM technologies.

Similarly, manufacturers and industrial customers raised concerns about digital infrastructure for **secure** (end-to-end) **data transfer** for decentral AM, particularly for IP-relevant applications. They emphasized that technical solutions must enable them to control who accesses the digitally encapsulated product specification remotely, how often parts are replicated from specific data, and ensure data format compatibility, reliable data interfaces, and real-time monitoring. Setting up such digital infrastructure for decentral AM is investment-intensive. Our interviewees considered it as even more essential than the physical infrastructure for AM and a barrier for decentralization. For instance, one industrial customer commented, "Without software in place and a database, decentral AM cannot grow. It is not possible." As a result, sufficient manufacturing volumes for decentral AM are necessary to justify the high investments of manufacturing firms in secure digital infrastructure for decentral AM.

In addition, we found economies of scale-based arguments related to the expertise that manufacturing firms currently build in AM for their applications. **Expertise pooling** is raised as a common argument for central AM operations. For example, one component manufacturer formulated, "AM know-how is shared […] in expert groups. This is where we manage to bundle it and achieve synergies." Similarly, we observed that experienced manufacturing firms often developed know-how in competence centers or specialized teams before replicating AM operations decentrally. As long as AM remains a set of specialized technologies, pooling expertise is necessary for learning.

**Market potential**

Decentral operations are more responsive to demand (Choi & Hong, 2002). The specific characteristics of AM facilitate such decentral operations; they are beneficial when they create additional **customer value**. In interviews, we observed that decentral AM operations may substitute traditionally centralized manufactured parts to ensure rapid part availability at remote locations. They enable manufacturing firms to manufacture necessary parts locally, omitting transportation lead times. One end-product manufacturer highlighted how this benefit of decentralized AM outweighs procurement costs, "Sending the spare part around the world is complete nonsense regarding lead time. In this case, money is less important than the lead time." This is also true in situations where customs may delay transportation. Such delays can be avoided by manufacturing additively on a local machine. Interviewees also reflected that decentral AM can be used to manufacture "temporary fixes" while waiting for the delivery of the original spare part, as similarly reported by Westerweel et al. (2021).

However, fast part availability is less needed in serial production, where reliable production planning exists and enables **efficient logistics**. A part may be pre-ordered and shipped efficiently to a location, thereby reducing the benefits of decentral AM. One AM service bureau shared, "Logistics processes are so efficient that if you ship a part today, it will be with the customer the next morning. Currently, I see no benefit of decentralization." Hence, AM enables decentralized operations to enhance customer value, but we found that it may be more efficient to centralize AM when production is stable and transportation is reliable and fast. As a summary, Table 7-1 presents the rationales (R) for the geographic dispersion of AM SCs.

Table 7-1: Rationales for the geographic dispersion and governance structure of AM SCs.

| Aggregation | AM factor | *Influence on …* | Effect |
|---|---|---|---|
| | | ***… decentralization of the AM SC*** | |
| Economies of scale | Machine utilization | R1: Need for sufficient and constant decentral demand for ensuring high machine utilization and reliable quality of manufactured parts | – |
| | Pre- and post-processing | R2: Need for space, labor, and equipment for pre- and post-processing at the decentral location | – |
| | Secure data transfer | R3: High investments in secure digital infrastructure for decentral AM (end-to-end data transfer, access control, data format compatibility, reliable interfaces, and real-time monitoring) | – |
| | Expertise pooling | R4: Need to bundle expertise centrally for learning at the emerging stage of technology development | – |
| Market potential | Customer value | R5: Demand for spare parts at remote locations | + |
| | | R6: Increased availability of decentrally manufactured spare parts by omitting transportation lead times | + |
| | | R7: Ability to manufacture "temporary fixes" for downtime reduction | + |
| | | R8: Possibility to bypass customs delays | + |
| | Efficient logistics | R9: Reliable production planning and efficient logistics for serial production | – |

Table 7-1 continued.

| | | ***… outsourcing in the AM SC*** | |
|---|---|---|---|
| Control | Quality | R10: Geographic proximity of the outsourcing partner creates trust and limits quality concerns | + |
| | | R11: No considerable quality concerns for parts with low requirements (e.g., first pilot studies) | + |
| | | R12: A lack of standards for quality control since testing procedures are currently developed individually in firms | – |
| | Certification and liability | R13: Nontransparent and tedious certification processes require long-term outsourcing agreements | – |
| | | R14: A lack of a clear-cut legal framework for the transfer of liability in AM outsourcing relationships | – |
| Core competencies | Digital product specification | R15: Encapsulated core competencies in the digital product specification (design, material, and process specification) | – |
| | | R16: Perceived inefficiency to protect IP and fear of opportunistic behavior (copying and counterfeiting) | – |
| | Commitment to emerging technology | R17: High risk of obsolescence of AM machines | + |
| | | R18: Variety of AM technologies/materials and the ability of AM service bureaus to specialize and develop expertise | + |
| | | R19: Shortage of AM specialists available in the nascent market | – |
| | | R20: Benefits of early market entry for learning and outpacing competitors | – |
| | | R21: Enthusiasm of senior management for AM and willingness to take higher risks for investments than for traditional manufacturing | – |

\+ Supportive.
\- Constraining.

### 7.4.2.2 Governance structure

#### Control

When activities are outsourced to a supplier, mechanisms must be in place so that customers can rely on receiving the expected quality. If enforcing such controls is costly, vertical integration is suggested (Williamson, 2008). AM product **quality** control is challenging. Quality procedures are currently lagging behind technological development. An AM platform provider commented that their customers request rigorous quality processes developed for traditional manufacturing, like the Production Part Approval Process (PPAP) for automotive SCs. Meeting such processes with AM is challenging: “If you want to do a proper PPAP, you have to produce 500 parts in a trial run. And you do not use AM to order a large batch and throw parts away that you do not need.” As long as quality control has yet to be simplified while the technologies develop, manufacturing firms tend to produce complex parts in-house. For now, they enforce reproducible quality for industry-ready parts by individually developed test procedures. However, interviewees shared less quality concerns for parts with lower technical requirements like prototypes. In such cases, in-depth quality assessment is substituted by trust in AM service bureaus. Interviewees indicated that geographic proximity fosters trust by allowing personal contact and easier coordination of outsourcing.

Furthermore, the **certification** of materials and safety-relevant parts for AM is a nontransparent, tedious process. Interviewees shared their experience: Certifying new AM materials in aerospace may easily take three to five years, and up to about two years for safety-relevant rail parts. Thus, to support a supplier in obtaining the necessary certificates, the manufacturing firm needs to trust in a long-term outsourcing agreement to offset this investment. This situation is aggravated for decentral AM where extensive testing is not an option due to low volumes and missing equipment. In addition, product **liability** for AM parts has not yet been fully defined. The issue of a legal framework was raised by multiple industrial customers among our interviewees who considered using AM spare parts to replace traditionally manufactured parts. They are afraid of putting the product guarantee by the original equipment manufacturer (OEM) at stake, for example, when logistics service providers additively manufacture spare parts for their warehouse automation. In this vein, one industrial customer emphasized, “If we use the AM spare part and something else breaks in the system […], the OEM will not take any responsibility.” In summary, firms face uncertainty about the transfer of liability in AM partnerships and face major obstacles in obtaining certification for their components and end products. As a clear-cut legal framework has not yet emerged, manufacturing firms avoid outsourcing complex AM parts that carry a high risk of liability issues.

**Core competencies**

Firms have an interest in keeping their core competencies in-house (Prahalad & Hamel, 1990). During our interviews, we noted that manufacturing firms are currently reevaluating their core competencies in view of AM. We also observed that they may explicitly choose to rely on outsourcing partners when technological variety forces them to focus their AM activities on specific technologies. AM knowledge and expertise are encapsulated in the **digital product specification**, which contains not only the value-creating design file but also the selected material and customized process parameters (e.g., layer thickness, manufacturing speed and temperature). Creating the digital product specification requires specific and rare design and engineering skills. A software provider for AM shared, “Anyone can buy an AM machine, set it up, and produce. You can only differentiate yourself through the design and the know-how you invest in the design.” Early AM implementers among our interviewees argued that core competencies embedded in the digital product specification must be protected as they create a competitive advantage, and, hence, strongly plead for in-house production. Thus, a key argument for in-house AM is that of protecting their IP – and manufacturing firms raised the thought that AM holds significantly more IP than traditionally manufactured parts, even more so when design improvements are achieved through AM. We identified two manufacturing firms in our interviews that reintegrated previously outsourced parts in the transition from traditional manufacturing to AM. Their fear of copying and counterfeiting appears more pronounced for AM parts than for traditionally manufactured parts. Interviewees are not convinced that standard contracts and nondisclosure agreements are efficient in securing their IP. One end-product manufacturer shared, “AM is a digital manufacturing technology. Everything digital is easy to copy.”

Concerns are increased as AM technologies and materials are rapidly developing. Entering this arena requires a significant **commitment to emerging technology**: financial investment, paired with an uncertain market environment, and a high risk that a specific technology may become obsolete fast. In light of the technological uncertainty, the enthusiasm of senior management is a prerequisite for committing to in-house AM early. Interviewees pointed out that a strong belief in the potential of AM and a willingness to take higher risks for financial investments favor in-house AM. Firms’ investments are driven by the perceived potential of AM to outpace competitors. In this regard, several interviewees stated that they wanted to invest early and create expertise gaps compared to competitors. One SME component manufacturer formulated, “If we deal with AM today, we are well prepared to serve this […] market tomorrow.” This strategy may also defer market entrance by outside competitors. In contrast, AM industry experts and AM service bureaus shared their observation with us that overenthusiasm may lead manufacturing firms to invest too fast in in-house AM technologies.

Interestingly, we also heard opposing arguments for outsourcing from manufacturing firms. These manufacturers perceive that they cannot handle the immense variety of industrial AM technologies and materials in-house. Firms respond by collaborating with AM service bureaus that specialize in specific technologies and/or materials, creating a mutual lock-in (Holcomb & Hitt, 2007). Given that expertise for specific AM technologies is rare, we observed that the choice of partners is not location-driven but expertise-driven in such situations. Again, Table 7-1 summarizes the rationales (R) for the governance structure of AM SCs.

#### 7.4.2.3 Embedding in existing supply chain context

We observed that manufacturing firms' AM SCDs must be compatible with the existing SC context in which they are embedded. We heard strong arguments that the operational processes, firm characteristics, and industry "tradition" constrain the AM SCD decision regarding the willingness and readiness to decentralize and outsource AM activities.

**Process level:** Multiple interviewees argued that AM for a specific component will remain one process among many others in producing a system. For instance, one component manufacturer commented, "Our business is to assemble complete systems with several individual components. If I am not additively manufacturing the entire system, the rest remains traditionally manufactured. I still have to manufacture tools […], and I still have additional logistics processes." As a result, AM oftentimes does not substitute entire SCs, but rather manufacturing processes of individual components to complement traditional manufacturing, as also noted by Rylands et al. (2016). When the final system is created in a series of outsourced manufacturing processes, AM is likely to be outsourced as well. The necessary interfaces that facilitate outsourcing AM are in place. Similarly, a centrally manufactured part will most likely benefit from central AM. Hence, decentral AM is particularly attractive for stand-alone parts that can be entirely manufactured additively. While this limits the range of applications, it again fosters the importance of AM for spare parts (see, e.g., Braziotis et al. (2019) for stand-alone AM spare parts in the aerospace industry).

**Firm level:** We found that the AM SCD choice needs to be compatible with firm characteristics like size and age. Larger firms are more likely to have global subsidiaries and distribution structures, reducing setup costs for the decentralization of AM in a firm-owned network. An AM industry expert commented, "For a firm that produces nationally or regionally, the efforts might outweigh the benefits of decentralization." In addition, a global customer base will increase the customer value created by decentral AM. Furthermore, young firms may be faster in exploiting the benefits of decentral AM, as their structures are less established than those of older firms. Several interviewees expect young firms to "grow up with AM" and naturally align their operations to the requirements of AM.

**Industry level:** SCs differ by industry in terms of their institutional constraints and structures (Ghobadian et al., 2020), and we observed that this also impacts AM SCD. For example, the rail industry is generally known to be more decentralized than the automotive industry. This also holds for rail maintenance, repair, and overhaul that are distributed to accommodate the rolling equipment. One manufacturer of rail transportation equipment highlighted, "You do maintenance where the customer is," and this familiarity with decentralized operations fosters decentralized AM. Moreover, product characteristics (e.g., the product weight) that are given or typical for an industry can hinder the decentralization of AM. For example, one end-product manufacturer of heavy machinery emphasized that products weigh up to 440 tons and are typically immobile in its industry. In a similar vein, industries already differ in their level of outsourcing. Consider the example of rail versus automotive and aerospace. The rail industry traditionally tends to have high vertical integration, comparably few component manufacturers, and overlapping roles of buyers and suppliers. In contrast, the automotive and aerospace industries believe in extensive outsourcing, which is reflected in a clear division in end-product and component manufacturers. Interviewees expect the same to manifest for AM in the long term, even though OEMs in the automotive and aerospace industries initiated AM activities and currently develop expertise in-house. Their current AM activities may enable them to obtain knowledge to efficiently outsource the activities at the mature stage. In this sense, one component manufacturer formulated the requirements for establishing AM outsourcing in the aerospace industry, "If the OEMs have mastered AM, assessed AM, and the volume pays off, then they will certainly outsource." Actors from the AM domain mirrored this view. They expect the OEMs to go back to their traditional SCs and not become AM specialists once AM is a set of "normal" (qualified, certified, regulated) manufacturing technologies. This could be realized by selling their AM competence centers as spin-offs or subsidiaries to their traditional suppliers. Hence, we found industrial AM implementation in SCs to follow underlying industry patterns to a large extent.

## 7.5 Discussion

### 7.5.1 Theoretical contribution

Based on real-world insights collected from the industrial AM domain, this study provides a nuanced understanding of why each of the four polar AM SCD configurations is a suitable structure for manufacturing firms. Each AM SCD configuration is the outcome of a combination of the rationales of manufacturing firms at a specific point in their AM implementation, for specific AM applications, and in a specific SC context. Hence, in sum, the configurations emerge as value-creating structures that are aligned with the characteristics of AM and fit manufacturing firms' current strategies. Figure 7-6 disentangles the identified rationales for the four configurations and thereby summarizes the overarching decision patterns of manufacturing firms for selecting each configuration that emerged from our case study.

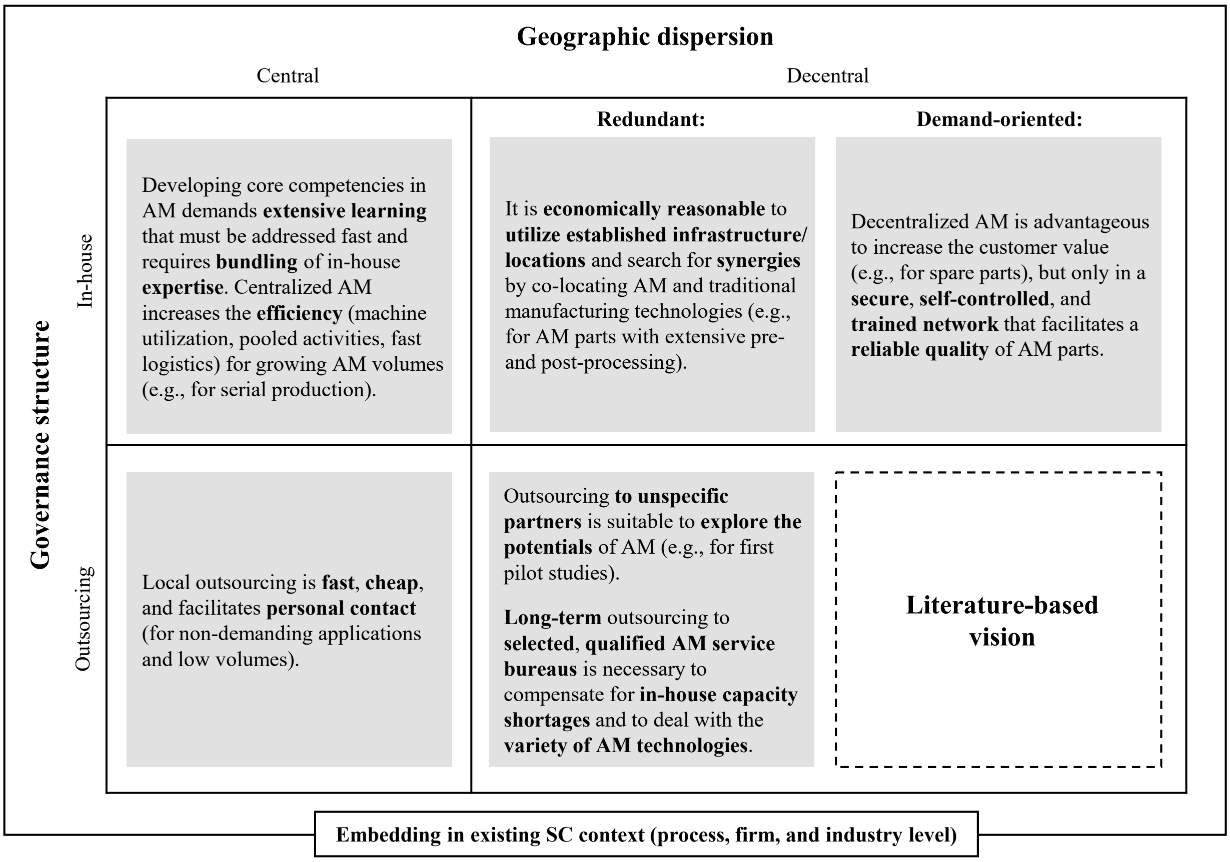


Figure 7-6: Rationales for the AM SCD configurations.

By developing an in-depth and context-specific understanding of the underlying rationales of the four cohesive AM SCD configurations, this study extends and refines existing knowledge and contributes new knowledge to the nascent literature stream of how AM impacts the SCD (e.g., Durach et al., 2017b; Verboeket & Krikke, 2019).

For the **geographic dispersion**, our findings reveal that if economies of scale cannot be achieved, the market potential of AM must be sufficient to outweigh the additional costs for decentralized operations. Increasing spare part availability brings such market potential, and we found that it goes beyond the idea that AM creates value when it offsets excessive inventory holding costs for intermittent (spare) part demand (Heinen & Hoberg, 2019; Song & Zhang, 2020). Our findings indicate that manufacturing firms have started to select decentralized configurations despite higher procurement costs. These firms benefit from the value created by omitted transportation lead times (R6), downtime reduction by manufacturing "temporary fixes" (R7), and bypassing of customs delays (R8).

The choice of centralized configurations, however, is dominated by arguments based on economies of scale (R1) and reliable and fast planning and transportation, for example, for the application of industrial AM in serial production (R9). Our interviewees emphasized the necessity of batch planning for the AM build volume, as also raised by Baumers and Holweg (2019), and of manufacturing the same parts in one build for reliable product quality. Recent studies neglect this potential quality risk when postulating an unlimited variety in AM build volumes (Durach et al., 2017b; Rogers et al., 2016), economic manufacturing of small volumes or even "economies of one" (Berman, 2012; Luomaranta & Martinsuo, 2020; Olsen & Tomlin, 2020), and the general-purpose characteristics of AM (Holmström et al., 2016; Holmström & Partanen, 2014). Moreover, in line with literature-based reasoning (Khajavi et al., 2014; Mellor et al., 2014), our findings indicate that in its present state, industrial AM is labor-intensive and far from full automation. Interviewees used economies of scale-based arguments to describe that industrial AM, particularly metal AM machines, currently require significant investments for equipment-intensive pre- and post-processing (R2), secure digital infrastructure (R3), and available AM-specific expertise (R4). Our observations reflect that interviewees are convinced that this expertise must currently be developed centrally. The identified rationales for expertise pooling relate to Ben-Ner and Siemsen's (2017, p. 17) argument that firms need "economies of scale in knowledge" at the emerging stage of technology development. Moreover, the organizational structures mentioned by interviewees for establishing AM centrally (e.g., in competence centers) are in line with Roscoe et al. (2019), who recommend bundling AM outside the authority-based structure of firms for flexible trial-and-error learning and knowledge exchange. With developed AM expertise, we observed that standardizing and replicating AM at pre-existing decentralized locations of firms becomes feasible.

Hence, even though AM machines are coined as compact, transportable production units that rely on basic raw materials (Kumar et al., 2020; Verboeket & Krikke, 2019), we found many rationales that show why, thus far, industrial AM cannot be flexibly located in the SC, in particular, metal AM machines. As a result, the rationales for the geographic dispersion draw a picture that significantly differs from the literature-based vision of limited relevance of economies of scale and location-independent AM. Expected advancements, for instance, increased automation of pre- and post-processing, established and accepted solutions for secure data transfer, and spread AM expertise, will likely simplify decentralized AM. However, sufficient demand for the efficient utilization of AM machines remains a constraint for industrial AM. A likely long-term outcome that is reflected in both our interviews and the literature is the bundling of demand from a regional market in a hub AM SCD configuration (e.g., Holmström et al., 2010; Khajavi et al., 2018).

For the **governance structure**, we found mutually supportive arguments for core competencies and control. Firms feel that they face an extensive learning task that they must address quickly at the current emerging stage of AM. They build in-house competencies to master AM and outperform competitors in the future, even though the return on the competency investment is highly uncertain and technologies might be outdated fast (R20, R21). The commitment to AM of senior management emerged as a prerequisite of these rationales in our interviews, as similarly recognized for AM by Schniederjans (2017). Rylands et al. (2016) emphasize that the enthusiasm of senior management can filter through organizations and establish a positive culture for AM. We noticed such positive culture when it comes to the novel design opportunities of AM, but also experienced that there is a fine line between enthusiasm and inflated expectations of senior management, potentially leading to overly fast in-house investments.

Moreover, we found that manufacturing firms reevaluate their core competencies and see significantly more IP in AM parts than in traditionally manufactured parts. AM becomes a field where firms want to build a competitive advantage, and this is contrary to the idea that outsourcing AM is beneficial as firms can leave it to the suppliers and focus on their core competencies independent of AM (Holmström et al., 2017). In light of the digital nature of AM, we experienced that AM brings forth extensive IP concerns (R15, R16). Firms refrain from outsourcing as the digital specifications are considered to contain core know-how. Hence, the ease of seamlessly transferring the digital product specification to outsourcing partners (Berman, 2012; Hedenstierna et al., 2019; Ruffo et al., 2007) is seen in our interviews as a risk of IP loss when outsourcing. According to Massimino et al. (2018), this tension between the benefit and risk is a paradox that applies not only to AM but to digital assets in general. Moreover, without standards and a clear-cut legal framework, individual specifications in every outsourcing relationship increase transaction costs and require long-term collaborations (R12–R14), as similarly expressed by Thomas-Seale et al. (2018).

In summary, the identified rationales lead firms to focus on in-house configurations at a central level or distributed activities in secure, firm-owned networks. Outsourcing configurations are selected in the early phase of AM implementation as a low-complexity entry (R10, R11) or as a necessity in light of the variety and rapid development of AM technologies (R17, R18), driven by the expertise of outsourcing partners and not their locations (R19). Outsourcing partners are carefully selected and audited; hence, outsourcing relationships are specific, just like for traditional manufacturing technologies. This contrasts with the vision of "generalized" and exchangeable outsourcing partners in AM that are available on the labor market (Ben-Ner & Siemsen, 2017; Holmström et al., 2016; Zijm et al., 2019). Thus, our findings provide a more nuanced picture than the literature-based expectation of flexible outsourcing to pools of AM service bureaus close to or even at the point of demand. We can draw from our findings that manufacturers will likely start to benefit from their outsourcing partners' decentral locations once a legal framework and standards are fully established, qualified AM service bureaus are more widely available, and the current urge of manufacturing firms to position themselves in AM fast is over. A crucial point that emerged from our findings lies in manufacturing firms' perceived risk of copying and counterfeiting their digitally encapsulated IP. Only with reduced IP concerns will the combination of decentralized and outsourced AM SCDs become feasible and enable increased sharing of decentralized AM capacities, for example, in regional AM hubs (Sasson & Johnson, 2016). For now, we find that manufacturing firms have valid reasons to select AM SCD configurations that differ from the literature-based expectations of decentralized AM and extensive outsourcing.

### 7.5.2 Managerial insights

With the provided in-depth insights into the AM SCD choice, our study supports manufacturing firms in integrating industrial AM in their SCs. First, it highlights which configurations are selected for specific AM applications and at specific AM implementation stages. Despite the tendency to in-house configurations, we see potential in a centralized, outsourced configuration as a natural entry point into AM. It enables firms to assess AM locally without making overly fast and risky technology investments.

Second, the rationales reveal the trade-offs and SC consequences of the AM SCD decision. They provide a clear perspective for manufacturing firms that consider decentralizing and outsourcing AM operations in their SCs. Furthermore, they enable manufacturing firms to evaluate their AM SCDs and position them within the matrix of geographic dispersion and governance structure.

Third, we emphasize that industrial AM SCD is embedded in the existing SC context. Hence, we create awareness that the impact of AM on SCD will remain limited in many cases. The geographic dispersion and governance structure of industrial AM will continue to be pre-defined by the locations and governance structures of the entirety of value-creating activities in the SC and their interplay. Moreover, the industry's tradition, its willingness and readiness to outsource and decentralize, and firm characteristics will continue to strongly affect AM SCDs.

## 7.6 Concluding remarks

Industrial AM is coined as an enabler of distributed manufacturing and lends itself to outsourcing manufacturing operations to suppliers. However, the current state of the industry is more nuanced. We applied a multiple-case study research design to explore four polar AM SCD configurations on the spectrum of geographic dispersion and governance structure. This approach enabled us to explore the rationales of manufacturing firms for selecting specific AM SC designs. We identified that the vision of decentralized, outsourced AM SCDs is unlikely to emerge as the "one-size-fits-all" SC structure for industrial AM.

Our findings are derived from individual interviews, thus, reflecting the viewpoints of firms and individuals willing to share their ideas. Specifically, they are based on insights gained from implemented AM SCDs of larger Western European manufacturing firms. Exploring AM SCDs of additional SMEs and manufacturing firms outside Western Europe will foster a more nuanced understanding once AM continues to mature and is more widely applied. Besides, our research is biased toward assuming manufacturing firms to be the focal entities in SCs, although we have taken the perspective of their potential suppliers and industrial customers into account and reflected their views. Based on our study, future work can give alternative emphasis to specific roles in SCs and extend the AM SCD configurations from the perspective of AM-specific suppliers, for example, the centralized, in-house configuration of AM service bureaus. For industrial customers, additional configurations for increasing "self-services" in potentially decentralized settings can be targeted in future studies.

Considering the empirical context, we build domain knowledge for industries that see a major benefit in industrial AM, which manifests in the prominent role played by quality control, certification, and liability in our findings. Constraints and traditions differ between these industries, which enabled us to gain nuanced insights into their AM SCDs and draw comparisons. However, for deeper and more specific domain knowledge, future work should focus on each of the targeted industries individually (i.e., the aerospace, rail, automotive, and machinery and equipment industries). Vice versa, for using the domain knowledge derived here as a basis for building a broader (instead of deeper) understanding of emerging AM SCDs, we suggest theorizing in other contexts. For this purpose, we foresee a need to adjust the configurations and rationales to the specifics of other contexts (e.g., the less regulated consumer industry) and propose this as a valuable next step toward more general theory building on AM SCD.

Furthermore, we have focused our exploration of the AM SCD decision and underlying configurations on a matrix of two dimensions, the geographic dispersion and governance structure. Refining these dimensions and considering additional dimensions would reveal further facets in the configurations and rationales. In particular, we have observed joint ventures, alliances, and acquisitions in industrial AM, and these hybrid governance structures could be integrated into our proposed structure of AM factors and underlying rationales.

Finally, AM is a set of emerging and inherently digital manufacturing technologies. Thus, our observed rationales are not necessarily AM-specific. On an aggregate level, we find that manufacturing firms tend to focus their AM activities on in-house, centralized, or secure decentralized operations in a firm-owned network. The reluctance to outsource and decentralize may be overcome to some extent as AM matures, supporting the idea that AM SC development is a long-term process (Durach et al., 2017b; Holmström et al., 2016; Verboeket & Krikke, 2019). We wish for follow-up research to explore similarities with other (manufacturing) technologies that share such characteristics and to monitor the future evolution and dynamics of the identified SCD configurations on the development path of industrial AM toward maturity.

## Appendix A: Information about the firms and conducted interviews

Table A7-2: Information about the firms and conducted interviews.

| SC actor | Firm | Product/ service | 2020 annual revenue (millions) | Number of employees | Location of the firm | Interview type | Job position of interviewee |
|---|---|---|---|---|---|---|---|
| End-product manufacturers | E1 | Machinery and equipment | $ 1,000–5,000 | 10,001–20,000 | Germany | Face-to-face° | Innovation Manager, Doctoral Candidate* |
| | E2 | Industrial conglomerate | > $ 20,000 | >100,000 | Germany | Face-to-face° | Head of AM |
| | E3 | Motor vehicles | n/a | n/a | Switzerland | Phone | Head of Technical Development |
| | E4 | Material handling equipment | $ 1,000–5,000 | 501–5,000 | Germany | Face-to-face | Director Digital Transformation |
| Component manufacturers | C1 | Basic metal | $ 1,000–5,000 | 5,001–10,000 | Germany | Face-to-face° | Head of Operational Excellence |
| | C2 | Motor vehicle components | $ 10–20 | 51–500⁺ | Germany | Face-to-face° | Senior Manager |
| | C3 | Rail transportation equipment | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | Vice President Spare Part Services |
| | C4 | Rail transportation equipment | $ 5,000–20,000 | 20,001–50,000 | France | Video | Chief Technology Officer |
| | C5 | Machinery and equipment | $ 100–500 | 501–5,000 | Germany | Phone | Head of Quality Management & Compliance |
| | C6 | Motor vehicle components | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | Head of Additive Technologies |
| | C7 | Machinery and equipment | $ 100–500 | 501–5,000 | Germany | Phone | Development and Technical Testing |
| | C8 | Aerospace equipment | $ 20–100 | 51–500⁺ | Germany | Phone | Vice President Business Development |
| Industrial customers (users of AM) | U1 | Passenger rail transportation | $ 5,000–20,000 | 20,001–50,000 | Italy | Phone | Network Logistics and Customer Manager |
| | U2 | Passenger rail transportation | $ 500–1,000 | 5,001–10,000 | Germany | Face-to-face | Head of Technical Development** |
| | U3 | Port logistics | $ 1,000–5,000 | 5,001–10,000 | Germany | Face-to-face | Head of Strategic Projects, Economist* |
| | U4 | Contract logistics | $ 100–500 | 501–5,000 | Germany | Face-to-face | Business Development Industrial |
| | U5 | Transportation services and contract logistics | > $ 20,000 | 50,001–100,000 | The Netherlands | Video° | Head of Contract Logistics |
| | U6 | Governmental organization | n/a | n/a | The Netherlands | Video° | Project Leader AM |

*Table A7-2 continued.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | U7 | Passenger and cargo rail transportation | > $ 20,000 | >100,000 | Germany | Phone | Plant Manager |
| AM service bureaus | S1 | Polymer and metal AM applications | $ 10–20 | 51–500⁺ | Germany | Face-to-face | Key Account Manager |
| | S2 | Metal AM applications | $ 1–10 | 1–50⁺ | Germany | Face-to-face | Managing Partner |
| | S3 | Polymer and metal AM applications | $ 20–100 | 51–500⁺ | Germany | Phone | Head of Marketing & Business Development |
| | S4 | Mobile AM micro-factory | n/a | 1–50⁺ | Norway | Video° | AM Expert** |
| AM machine manufacturers | P1 | AM machines for metals | $ 20–100 | 1–50⁺ | Germany | Face-to-face° | Sales Engineer** |
| | P2 | AM machines for polymers | $ 500–1,000 | 501–5,000 | Germany | Face-to-face | Technical Consultant |
| | P3 | AM machines for metal and polymers | $ 100–500 | 501–5,000 | Germany | Face-to-face | Business Development Manager |
| | P4 | AM machines for metals | $ 20–100 | 51–500 | Germany | Phone | Director Business Development |
| AM material supplier | M1 | Specialty chemicals | $ 5,000–20,000 | 20,001–50,000 | Germany | Face-to-face | Head of AM |
| AM software and platform providers | SP1 | Software for AM processes | n/a | 1–50⁺ | Germany | Phone | Managing Director |
| | SP2 | Software for AM design automation | n/a | 1–50⁺ | Germany | Face-to-face | Managing Director |
| | SP3 | Platform for matching orders and AM service bureaus | $ 1–10 | 1–50⁺ | The Netherlands | Video | Chief Operating Officer |
| AM industry experts | I1 | Established AM firm network | Nonprofit organization | 1–50 | Germany | Face-to-face° | AM Expert** |
| | I2 | Consulting firm for AM implementation | n/a | 1–50⁺ | Germany | Phone | Managing Partner |

+ SME.
° Two interviewers present.
* Two interviewees.
** Internal data provided.

## Appendix B: Semi-structured interview protocol for manufacturing firms

1. *Background information*
   a. Interviewee information (name, years in the firm, professional and educational background)
   b. Interviewee’s relation to AM (job description, responsibilities, connection to AM)
   c. Firm information (firm name, years in existence, size, number and distribution of firm locations, key products and services)
   d. Current SCs (major suppliers and customers and their geographic location)

2. *Firm's state of AM implementation*
    a. Start of AM activities (initiation of AM involvement, timeline, first activities, first AM applications, partners)
    b. AM implementation (developed structures and knowledge, collaborations)
    c. Current AM SCs (AM applications, specific suppliers for AM, customers for AM)
    d. Assessment of AM (current maturity of AM for firm's applications, expectations for AM in 10 years)
3. *AM SCD*
    a. How concrete are your firm's ideas regarding the integration of AM in your SCs?
    b. Which changes have you observed for your firm's SCs based on AM?
        - Changes in locations for production and warehousing?
        - Changes in inventory levels and production lot sizes?
        - Changes in transportation flows?
    c. How do you react or plan to react to these changes?
    d. Which competencies do you need or expect to need for AM?
    e. Which competencies for AM should stay within your firm (in-house) in AM SCs?
    f. Do you expect changes in your vertical integration?
    g. Do you see a need for new partners in AM SCs?
    h. Could you imagine more decentralized structures for your AM SCs (centralized versus decentralized strategy for AM)? Why do you expect/not expect more decentralized structures?
    i. Which long-term impact do you expect AM to have on SCs in your industry?
4. *Wrap up*
    a. What are critical milestones for the future development of AM SCs in your industry?
    b. If you could change one existing constraint/limitation, what would that be?

## Appendix C: AM applications and AM implementation stages of manufacturing firms per case

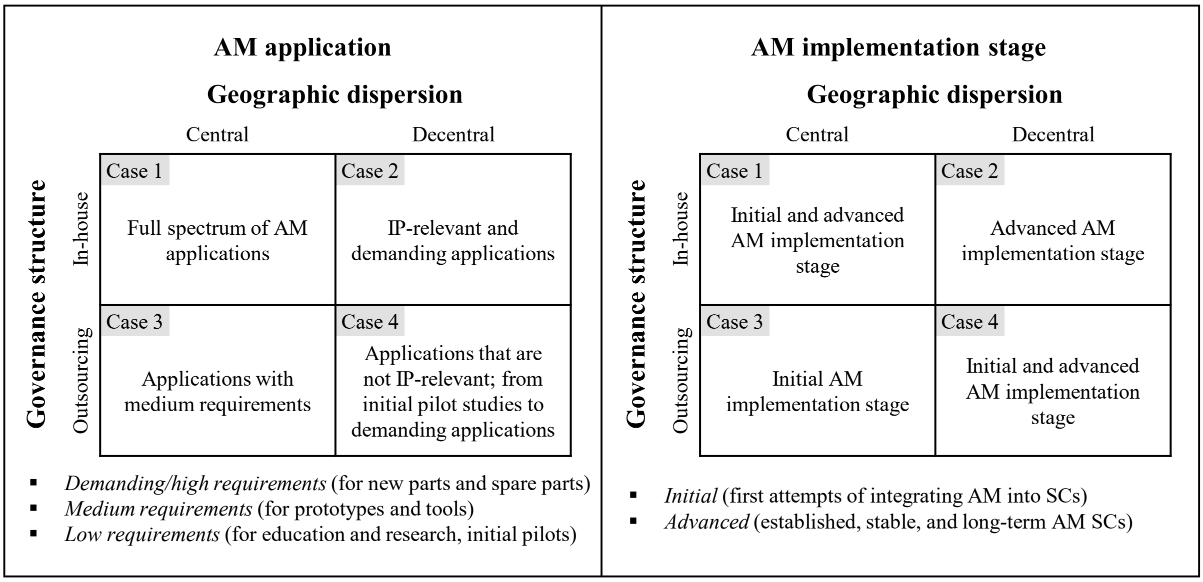


Figure A7-7: Comparison of AM applications and implementation stages per case.

## Appendix D: Representative quotes

Table A7-3: Representative quotes.

| Agg. | AM factor | Representative quotes |
|---|---|---|
| Economies of scale | Machine utilization | ▪ "Theoretically, you want to operate an AM machine 4,000 or 5,000 hours a year to be profitable. Then, you can also spend a million or half a million on it. Decentral, at the customer location, […] I do not see that such a capacity utilization is possible." (C8)<br>▪ "If you want to have a profitable investment, you need to be as efficient as possible. So, no cleaning of the AM machine for other types of materials. You run your AM machine with one type of material." (SP3)<br>▪ "If the AM service bureau combines different parts in the AM build volume, the manufacturing outcome will be slightly different every time." (M1) |
| | Pre- and post-processing | ▪ "You would need a lot of additional equipment at the decentral location for the following processes. This is not reasonable if you have manufacturing centers elsewhere." (E2)<br>▪ "[…] the equipment requires a high investment. You need space, labor, and processes. It is not just an AM machine." (C6)<br>▪ "I do not believe in extremely decentralized AM for the industrial sector. Because the quality process has to be ensured, the employees have to be trained, the maintenance has to be done, the material has to be there." (S1) |
| | Secure data transfer | ▪ "In any case, someone in the AM SC needs a software solution, someone needs to pay attention to [data] security." (E2)<br>▪ "We must ensure process reliability and real-time monitoring of the manufacturing process. Because someone has to say, 'Yes, everything worked well.' And AM is not yet at a stage where such a real-time monitoring is available." (C3)<br>▪ "We have to provide compatible interfaces. […] the entire data chain is ideally automated without any manual format conversions." (P3) |
| | Expertise pooling | ▪ "I think it makes sense to bundle and develop the competence centrally, and when a certain level of maturity is reached, it is possible to decentralize AM. […] AM is growing out of infancy, but still has some homework to do." (C6)<br>▪ "AM machines require technological know-how and this cannot be decentralized yet. A lot of operations are still centralized, particularly by creating specialized AM departments in large firms. That is where a lot of know-how is bundled, where all the experts are." (P2)<br>▪ "But it is still a specialized technology. You still need specialists to run your machines. […] it will take you one year and a half until a metal machine runs at 80%." (SP3) |
| Market potential | Customer value | ▪ "The advantage lies in the local and independent production of parts, for example, directly at the customer's location if a part fails. This will probably eliminate a large proportion of the current parts traffic." (C7)<br>▪ "During maintenance, a specific part got stuck in customs. This caused an incredible amount of extra downtime. So, […] it might be worth considering a mobile on-site micro-factory for AM." (S4)<br>▪ "If you have a broken part, you can download the temporary spare part from a platform and manufacture it. It will last at least until the original spare part arrives. Downtime is reduced. This is already possible for some polymer spare parts." (SP2) |
| | Efficient logistics | ▪ "We manufacture 6,500 AM parts for our customer per year and deliver the parts just-in-time to the production line where components are assembled." (E3)<br>▪ "The customer has to accept that it will take some days to produce a component because it is physics, it is a welding process that I cannot trick. I send the component with a logistics service provider and it is quickly at the customer in 24 or 12 hours." (S2)<br>▪ "You have to think carefully about becoming a local service provider for AM. Because AM parts can be sent anywhere." (M1) |

*Table A7-3 continued.*

| | | |
|---|---|---|
| Control | Quality | ▪ “We have a secure network that we can trust because we have built it up, trained it, and implemented a common quality standard. If we integrate a partner, then, we have to qualify him in order to trust him.” (C3)<br>▪ “Do I send orders to some decentral AM service bureaus where I have not done an audit, where I do not know the quality process? I do not see that for industrial AM.” (S1)<br>▪ “If I have some prototypes, I do not care who manufactures them. Because it just has to look good and be done.” (S3) |
| | Certification and liability | ▪ “We need to demonstrate that we can create structures with AM that meet the old standards. It is very, very complex. You need to be able to guarantee 100% reproducibility in aviation. This is why we have a hard time getting certifications fast.” (C8)<br>▪ “Certification [at remote locations] is very much based on ‘goodwill.’ You just have ad hoc tests that you can do to convince the users.” (S4)<br>▪ “You will not install an AM machine at the customer’s location and say, ‘You can manufacture your spare parts.’ It starts with liability, who is liable for such a part?” (C8)<br>▪ “Somebody has to take over the responsibility. The question is who will guarantee the quality of the output of the AM machine? That is still a technical problem.” (U5) |
| Core competencies | Digital product specification | ▪ “It is core know-how, which you would not like to transfer to a supplier and make him smarter.” (E2)<br>▪ “In addition to the pure CAD data, you also have to transfer the process data and manufacturing data to a supplier. […] I think it is difficult to protect all this know-how.” (C7)<br>▪ “Manufacturing firms increase their vertical integration because they are capable of producing very complex geometries and a high number of variants. […] there is a lot of design and process know-how in these components.” (I2) |
| | Commitment to emerging technology | ▪ “It is a question of how open-minded the management is toward new technologies. […] you first have to make an upfront investment.” (C7)<br>▪ “It is still an early phase, so it is really not easy to say how AM will change processes but we will be at the forefront.” (U3)<br>▪ “There are many technologies and no clear winner. […] you cannot buy an AM machine because there may be a new or better technology next year.” (U1)<br>▪ “Today, customers are looking for specialized AM service bureaus that can cover their requirements. But not many specialists are available at the moment.” (E3) |
| Embedding in existing SC context | Process level | ▪ “We are a system supplier. That means we assemble complete systems from several individual components. If I am not additively manufacturing the entire system, then, AM replaces only some components.” (C6)<br>▪ “AM accounts for maybe 15% of the value created with the ready-to-install part that we deliver to the customer.” (C8)<br>▪ “The actual AM process is just one building block in the whole big process chain, and I think you have to understand that first.” (SP2) |
| | Firm level | ▪ “Large firms can afford to invest in the technology without knowing the potential yet. Small and medium-sized firms need more certainty before they start.” (SP1)<br>▪ “Firms that already produce and sell globally anyway can decentralize AM. They can quickly switch to decentralized AM without transferring know-how to other countries.” (I1)<br>▪ “If it is a young firm, there is an interest and awareness of AM. But otherwise, I mean, never change a running system.” (P3) |
| | Industry level | ▪ “Railway manufacturers have significantly less suppliers than automotive manufacturers.” (C4)<br>▪ “I think it is a common behavior in the automotive industry that OEMs develop the technologies in-house, perfect the technologies, and then hand them over to their suppliers.” (I1)<br>▪ “I think OEMs mainly build know-how internally to assess whether their suppliers are capable of producing AM parts according to their quality standards. These big firms are trying to build a robust AM SC.” (P4) |

# 8 Overarching discussion and concluding remarks

This chapter aims to link the findings of the main body of this thesis (part A and part B) to the conceptual and theoretical-methodological frameworks. These frameworks have been motivated in Chapter 1, established in Chapter 2 and Chapter 3, and visualized with the CIMO-logic (Denyer et al., 2008). For this reason, this chapter starts with a reflection on the theoretical and practical contributions of this thesis in Section 8.1. It then revisits the overarching research questions RQA and RQB in Section 8.2 and discusses the findings in their light, which constitutes the primary purpose of this chapter. This chapter closes by summarizing overarching research limitations and future research directions in Section 8.3, structured along the conceptual and theoretical-methodological scope of this thesis.

## 8.1 Reflection on the theoretical and practical contributions

Industrial AM technologies are expected to disrupt the design of traditional SCs and revolutionize the way firms do business. The inherently digital and flexible technologies are praised for their potential to eventually enable SCs to move production to the point of demand and foster intensified outsourcing of manufacturing activities to local partners. This vision has been derived in Chapter 2, and its implications for LSPs' traditional business models and manufacturing firms' traditional SCD choices have been discussed in light of the extant AM business model and OSCM literature. However, the reality is currently more nuanced, and the four studies that comprise the main body of this thesis show why this is the case.

This thesis contributes to filling the **research gap** between visionary and often conceptual expectations from the literature and currently emerging realistic business models and SCDs for industrial AM. Overall, it stands out for deriving the presented findings from rich, real-world perspectives that have been deeply analyzed. Furthermore, this thesis demonstrates a strong focus on developing an understanding (instead of explaining), formalized in *how* and *why* research questions, to explore the rationales of manufacturing firms and LSPs. It further emphasizes the importance of taking a process-based perspective, particularly in study A.1, to build knowledge on how AM business models and SCDs are currently evolving as a basis for tentatively proposing their long-term outcomes. Finally, this thesis provides context-specific research, manifested in its embedding in the industrial AM context. It accounts for the specifics of this context to build domain knowledge. For AM itself, this thesis separates the effects of the inherently digital and emerging traits of the technologies to reveal how they affect firms' choices, foremostly manufacturing firms' AM make-or-buy decisions in study B.1.

From a **theoretical perspective**, the findings of this thesis contribute to building initial theory on emerging AM business models and SCDs and elaborating existing theory (TCE and the RBV) in the novel industrial AM context. Moreover, this thesis significantly enriches and refines the extant OSCM and business model literature with the developed nuanced understanding of the reactions and underlying causal mechanisms that currently drive manufacturing firms and LSPs in their AM implementation. On this basis, this thesis also offers **managerial insights**. To highlight a few key aspects, LSPs can use the developed taxonomy to classify existing and develop new AM activities (study A.1). They can further rely on the guidance provided for the question of which generic AM business model configurations create a fit for specific types of LSPs (study A.2). For manufacturing firms, this thesis demonstrates the advantages and risks of in-house AM versus outsourcing (study A.1) and the trade-offs involved in selecting specific AM SCDs (study A.2), which, in sum, raise awareness for alternative AM implementation paths. Next, the main findings of this thesis, which are the basis for the theoretical and practical contributions, will be discussed.

## 8.2 Discussion of the overarching research questions

This section discusses the two overarching research questions, RQA and RQB, addressed with the studies in part A (Chapter 4 and Chapter 5) and part B (Chapter 6 and Chapter 7) of this thesis, respectively. It also interprets how the studies within part A and part B relate to each other and, thereby, makes suggestions for their interplay, presented in summarizing figures. In addition, this section refers back to the concept of *fit*, which has been introduced as a central element of this thesis. It starts with discussing RQA in Section 8.2.1 and continues with addressing RQB in Section 8.2.2.

### 8.2.1 The impact of additive manufacturing on the business model development of logistics service providers

The role of LSPs is special in the AM business ecosystem based on their direct dependence on their customers' reactions to AM and their inherent adaptability to their customers' requirements in the highly competitive logistics market. Given the predicted impact of AM on the traditional business models of LSPs, the overarching research question RQA aims at developing an in-depth understanding for LSPs' AM-initiated business model development process and its outcome.

**RQA:** *How* and *why* does industrial AM impact the business model development of LSPs?

The two studies of **part A** have addressed RQA by building a comprehensive understanding of how LSPs currently react to industrial AM and consumer-oriented polymer 3D printing with specific AM activities. In addition, part A of this thesis has proposed empirically grounded business model configurations that have the potential to provide a long-term fit for specific types of LSPs. Combining the findings from both studies offers valuable insights into how LSPs' current activities can serve as a basis for business models in the AM business ecosystem. Hence, when summing up both studies, a line can be drawn from how currently observable AM business model dynamics could remain limited in their overall impact on LSPs' traditional business models or how they could lead to major business model changes and, ultimately, to the permanent coexistence of traditional and AM-based business models. Figure 8-1 illustrates this relationship by linking the two studies to the CIMO-logic and highlighting key results.

By taking a process-based perspective, **study A.1** provides a comprehensive overview of six profiles of how LSPs currently react to AM and polymer 3D printing based on 52 classified AM activities of 47 mostly large Western European LSPs. Overall, the identified profiles of AM activities show that LSPs currently see themselves in diverse roles: as passive and hesitant observers (Monitors), as users (Explorers, Co-Industrializers), and as emerging service providers in the AM business ecosystem (Traditionalists, Complementors, Intermediaries). Hence, study A.1 indicates that AM – as an intervention – triggers different mechanisms at LSPs, and the six profiles cover the currently observable spectrum. Furthermore, the derived profiles establish that specific types of LSPs approach AM differently, resulting from differences in their underlying reasoning (*why*) for initiating, intensifying, and discontinuing their AM activities: Standard LSPs turn into users of AM by relying on their manufacturing background from traditional MRO activities. Their reasoning for AM is driven by the motive of learning (internally and with partners) to achieve efficiency gains and foster advances in the industrialization of AM for applications from the logistics/transportation sector. In addition, the pressure to prepare for AM-based maintenance is reflected in the AM activities of standard LSPs since their equipment suppliers (e.g., train and aircraft manufacturers) increasingly integrate AM parts into their new products. Contract LSPs, with their strong customer orientation, either reactively wait for a "customer push" before initiating serious AM activities or actively prepare for their customers' needs in digital AM SCs. It can be seen in study A.1 that contract LSPs and CEP service providers stand out for their perceived pressure to react to AM in a fast and committed way. Study A.1 indicates that these LSPs initiate AM activities to counter expected losses in their traditional business and take part in the digital transformation. In addition, it is established as an overarching pattern in study A.1 that all types of LSPs are in a suitable position to start offering traditional logistics services for AM which constitutes a low-complexity AM market entry for them. Thus, transportation and warehousing services for standard/contract LSPs and consulting services for consulting LSPs emerge as obvious AM activities.

In summary, study A.1 demonstrates that four of the six currently observable profiles of AM activities entail changes in LSPs' traditional business models by fostering business model revisions, extensions, and creations. Thereby, AM is recognized as an exogenous driver that causes **business model dynamics**, as established in the business model literature for emerging, potentially disruptive technologies in general (see Section 2.2.1). However, for many of the observed AM activities, these initiated business model dynamics have, so far, a limited impact on LSPs' traditional business models since they are strongly based on traditional logistics resources (i.e., LSPs' logistics expertise and assets). Hence, study A.1 reasons that LSPs oftentimes select a "path-dependent" strategy (Cavalcante, 2013) for their AM business model development (see Section 2.2.1). Study A.1 shows how emerging AM business models complement or directly correspond to LSPs' traditional business models. They can be understood as slight adaptations or small business model changes that enable LSPs to rely on their past resource investments. Overall, the findings from study A.1 reflect that AM confronts LSPs with the fundamental question of whether to stick to their resource base or develop a new, potentially digitally oriented resource base for AM. The business model literature argues that novel, unfamiliar business models are more likely to enable firms to achieve or regain a sustained competitive advantage than slight variations of existing business models (Teece, 2018). However, study A.1 supports that novel "path-breaking" strategies for AM are certainly more challenging to implement and require LSPs to take financial risks and commit to a trial-and-error business model development process.

By taking a step from current business model dynamics (study A.1) to a narrower exploration of **"finished" business model configurations** for industrial AM (study A.2), viable paths emerge of how LSPs can continue to use their resource base or establish an AM-specific resource base. As illustrated in Figure 8-1, **study A.2** explores and critically evaluates with a business model lens six generic business model configurations as potential outcomes of LSPs' current mechanisms of dealing with AM. The logistician and orchestrator configurations summarize LSPs that continue to offer traditional logistics services for AM and/or orchestrate AM industry clusters at strategic infrastructure nodes like ports and airports. These LSPs continue their "path-dependent" strategy for AM. Business models that fundamentally differ from the traditional business models in the logistics industry can be expected from the manufacturer, agent, and consultant configurations. The manufacturer configuration fulfills the literature-based expectation of LSPs as manufacturers in AM (see Section 2.2.4). However, the perspectives collected in study A.2 from interviews with LSPs and their potential partners/competitors and industrial customers reflect that this positioning as a manufacturer in AM comes with serious doubts about the economic efficiency and the required expertise of LSPs, at least for industrial AM technologies. The landlord configuration emerges as a cooperative variant that counters these doubts but creates new challenges in the design of suitable revenue mechanisms. The consultant and, even more, the agent configuration stand out for their digital dominance and potential independence from LSPs' traditional logistics resource base.

Finally, when coming back to the **concept of *fit***, Section 2.2 has established that AM can create a *misfit* for LSPs' traditional business models. The extant literature expects AM technologies to foster more open, customer-centric business models that enable incumbents to offer interwoven product-service systems at locations close to or even at the point of demand (see Section 2.2.3). With manufacturing firms, as LSPs' typical customers, increasingly integrating AM into their business models, LSPs' core services are expected to be (at least partially) rendered obsolete. Section 2.2.4 has systematized the literature-based expectations for an overall reduced demand for logistics services (e.g., less global transportation, less transportation of semi-finished products) and highlighted the current lack of quantification of the impact of AM. It has further structured the literature-based expectations for sustaining logistics services in AM (e.g., transportation of raw materials and efficient logistics solutions for the last mile). On this basis, Section 2.2.4 has proposed visions of "finished" AM business models of LSPs, which are mostly conceptually derived. In comparison, the cohesive business model configurations of study A.2 provide real-world insights into how LSPs can regain a fit in the industrial AM business ecosystem and balance losses in their traditional business. As depicted in Figure 8-1, the logistician and orchestrator configurations enable standard and contract LSPs to take advantage of the remaining need for logistics services in industrial AM SCs. The manufacturer and landlord configurations demonstrate how LSPs can adapt their internal structures (i.e., their mechanisms for creating and capturing value) and competitive strategies to fit into the picture of shorter, decentralized AM SCs. Indeed, study A.2 establishes that, with AM as value-added services at their warehouses and distribution centers, the manufacturer and landlord configurations offer contract LSPs the opportunity to directly contribute to the decentralization of SCs. The agent and consultant configurations are consistent with the increasing dematerialization in digital AM SCs. In particular, the agent configuration highlights the opportunities for LSPs to develop platform-based AM services that distinguish themselves by their novelty.

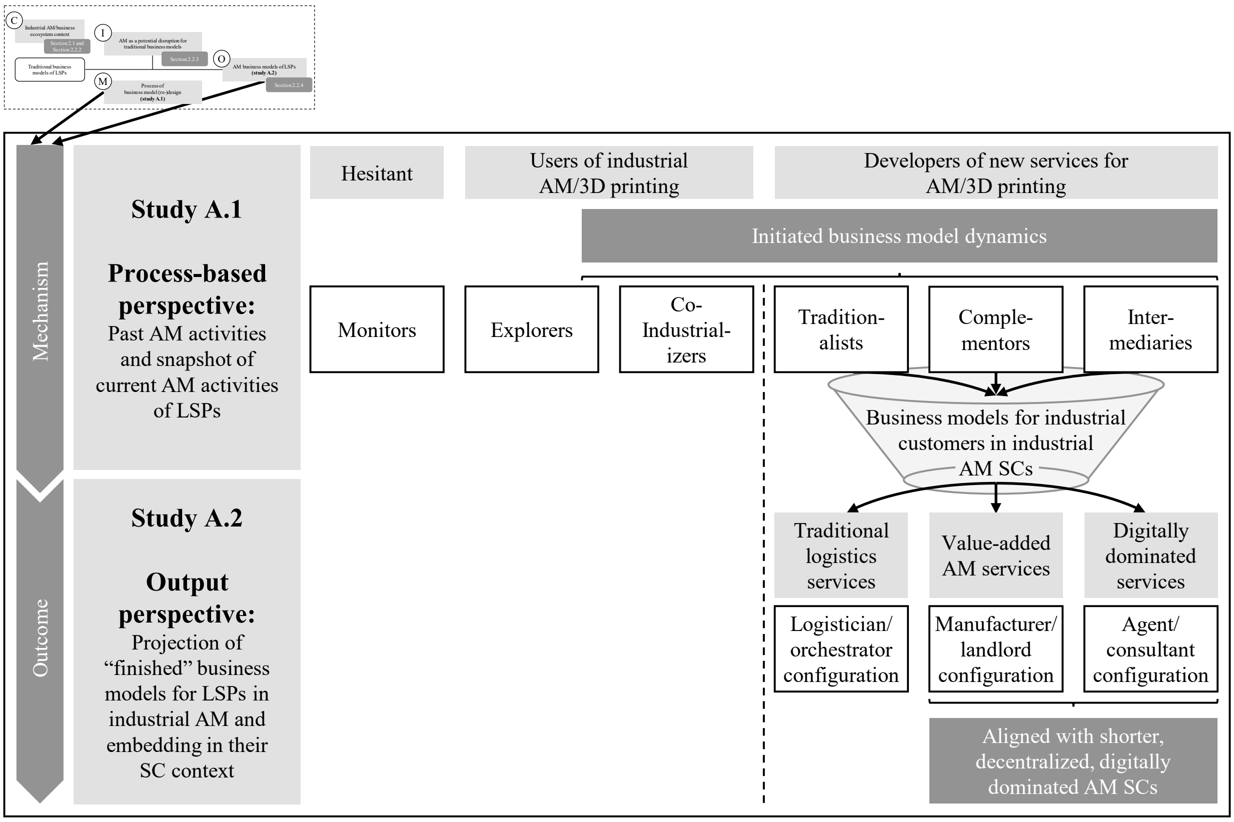


Figure 8-1: Summarized findings for the overarching research question RQA.

### 8.2.2 The impact of additive manufacturing on the supply chain design choice of manufacturing firms

With incumbents adapting their business models to AM and consequently their SCs, the overarching research question RQB has been formulated to investigate the rationales behind the AM SCD decision.

**RQB:** *How* and *why* does industrial AM impact the SCD choice of manufacturing firms?

To address RQB, studies B.1 and B.2 of **part B** of this thesis have been embedded in the industrial AM context to develop a domain-specific understanding. The studies focus on the perspective of focal manufacturing firms as the dominant decision-makers in SCs, as established in Section 2.3.1. Moreover, in Section 2.3.1, two dimensions have been introduced to characterize AM SCDs, the horizontal scope (geographic dispersion) and the vertical scope (governance structure). Study B.1 has taken a firm-centric perspective to develop an in-depth understanding for AM make-or-buy decisions of manufacturing firms, the outcomes of which determine the governance structure. On this basis, study B.2 has shifted from a firm-centric to a network perspective to make use of both dimensions for exploring cohesive AM SCD configurations. When considering the introduced CIMO-logic, studies B.1 and B.2 focus on the mechanism of (re-)designing SCs and the involved inner causal processes of manufacturing firms. As visualized in Figure 8-2, they do not aim to investigate the expectations for the outcome of this process, as dominant in the extant literature. Instead, the studies investigate the rationales of focal manufacturing firms in their current process of (re-)designing and adapting their SCD choices as a reaction to the intervention of AM.

**Study B.1** finds that manufacturing firms currently approach **AM make-or-buy decisions** differently from what is known from traditionally “analog” manufacturing technologies. Based on collected empirical data from 12 manufacturing firms, study B.1 finds four AM make-or-buy decision profiles to classify the observed behavior of the 12 cases of manufacturing firms. These four decision profiles show that, beyond aspired outsourcing (Waverers), strong tendencies exist to invest in in-house AM (Pioneers), to purposively combine in-house AM and outsourcing (Combiners), and the intention to do so in the future (Planners). The four identified profiles provide insights into how manufacturing firms currently approach AM make-or-buy decisions. To understand why AM often drives them toward hierarchical governance (in-house AM), study B.1 develops across the cases a framework for AM make-or-buy decisions with additional insights from context-specific data collected from actors from the AM domain. This framework is schematically displayed in Figure 8-2. It disentangles the rationales behind AM make-or-buy decisions. In doing so, study B.1 shows how the specific characteristics of AM, the digital and emerging traits of the technologies, modify general factors. These general factors can be explained following established arguments from TCE and the RBV. The digital traits are represented by the digital product specifications, namely the digitally encapsulated design and manufacturing know-how in AM. In a nutshell, the digital traits increase manufacturing firms’ IP concerns in AM and initiate the reevaluation of their core competencies. The emerging traits further aggravate the situation by encouraging manufacturing firms to make investments in AM capacities and skills and to cautiously manage dependency in their outsourcing relationships. Study B.1 provides in-depth insights into the underlying arguments and, with that, draws an overall picture of why multiple rationales drive manufacturing firms toward in-house AM at the current emerging stage. These results contrast with the literature-based vision outlined in Section 2.3.4. The literature expects the digital traits of AM to foster and ease both the outsourcing of the AM process and the sharing of commoditized manufacturing infrastructure. In contrast, AM outsourcing emerges in study B.1 as an active choice that is restricted to selected and audited partners and to applications that do not contain significant IP. As a result, identified opportunities for outsourcing industrial AM are limited to the early stage of AM implementation, the motive of gaining access to specialized AM technologies, and to demand exceeding in-house capacities.

By lifting the governance choice from a firm-centric to a network perspective and combining it with the geographic dispersion, **study B.2** establishes a matrix for exploring **polar AM SCDs**. The study characterizes four cases of cohesive AM SCDs, each representing one field of the matrix, as illustrated in Figure 8-2. Based on empirical insights collected mostly from focal manufacturing firms and reflected by AM-specific suppliers and industrial customers, study B.2 builds an understanding for each of the four configurations. On this basis, study B.2 analyzes across the four cases in order to develop a data structure exploring the rationales behind the emerging four AM SCD configurations. Figure 8-2 schematically visualizes the outcome of the developed data structure, consisting of ten AM factors and their literature-based aggregation (economies of scale, market potential, control, and core competencies). In summary, study B.2 finds for the geographic dispersion that if economies of scale cannot be achieved, the market potential of AM must be sufficient to outweigh the additional costs for decentralized AM. Thus, manufacturing firms face a trade-off between the customer value (e.g., for rapidly available spare parts due to decentralized AM) and losses in economies of scale in decentralized settings (e.g., for an insufficient utilization of AM machines, pre- and post-processing equipment, and digital infrastructure as well as for the inability to pool expertise). Regarding the governance structure, study B.2 finds that the consolidated arguments for control and core competencies are mutually supportive. If manufacturing firms' core competencies are affected by AM, high requirements for ensuring stable and reproducible product quality and obtaining certifications can only be met in-house. In combination, the reasoning for the two dimensions, the geographic dispersion and governance structure, leads manufacturing firms, at the current emerging stage, to focus their AM activities on in-house SCDs at a central level or distributed in secure firm-owned networks. Outsourced configurations are chosen in the early stages of AM implementation or as a necessity, given the diversity of AM technologies. With that, study B.2 establishes that outsourcing partners are currently rare and strictly selected by their expertise and not by their decentralized locations. As a result, the expected combination of a decentralized, outsourced configuration remains visionary for now and cannot mirror industrial practices yet.

Returning to the **concept of *fit***, Section 2.3 has given reasons for the expected power of AM to initiate or necessitate the (re-)design of traditional SCs. Typical traditional SCs have been characterized as long, global, and complex structures that consist of multiple, highly specialized firms. Identified literature-based expectations for the outcome of the AM-initiated process of (re-)designing such traditional SCs point to a shift from centralized to decentralized SCs. These shorter and more resilient SCs are expected to hold multiple opportunities for outsourcing manufacturing activities to pools of local AM service bureaus (see Section 2.3.4). Indeed, the studies B.1 and B.2 demonstrate that manufacturing firms perceive industrial AM as a potential source of *misfit* for their established SCDs. Their reactions to AM are currently strongly driven by the digital and emerging traits of AM, as elaborated in detail for AM make-or-buy decisions in study B.1. However, the two studies argue for a spectrum of value-creating AM SCDs besides the vision of decentralized, outsourced AM SCDs. Specific configurations from this spectrum fit specific competitive strategies of manufacturing firms at the current emerging stage of AM: Study B.2 finds that a centralized, in-house configuration creates consistency between structure and strategy for manufacturing firms that intend to develop core competencies and scale up AM for increased efficiency (e.g., in serial production). Decentralized, in-house AM enables manufacturing firms to successively standardize, reproduce, and distribute AM for economic reasons (e.g., for creating synergies in pre- and post-processing activities). Such a distribution of AM in a secure firm-owned network can ultimately enable strategic decentralization to approach the point of demand (e.g., for reduced lead times based on AM in firm-owned maintenance plants). Moreover, the centralized, outsourced configuration holds the potential to be a fast and easy option for non-demanding applications (e.g., for prototypes). The outsourcing to potentially multiple, decentralized AM service bureaus emerges as a suitable market entry (e.g., for first pilot studies) and as an opportunity for long-term outsourcing of AM to a strategic network of selected partners.

Finally, SCs have been introduced as **"configurable systems"** in Section 2.3.1, and the results of studies B.1 and B.2 indicate that manufacturing firms opt for different designs for specific AM applications at specific stages on their AM implementation path. However, multiple arguments, in particular in study B.2, provide evidence that the AM SCD choice is constrained, at least in the long term. Study B.2 raises awareness that AM implementation is expected to follow established patterns. In many cases, industrial AM currently does not substitute entire SCs but rather individual parts and complements traditional manufacturing. Hence, study B.2 establishes that AM needs to be integrated into existing processes, firm structures, and, in the long term, follow established industry traditions. Following these patterns constrains the choice of the AM SCD on the spectrum of geographic dispersion and governance structure.

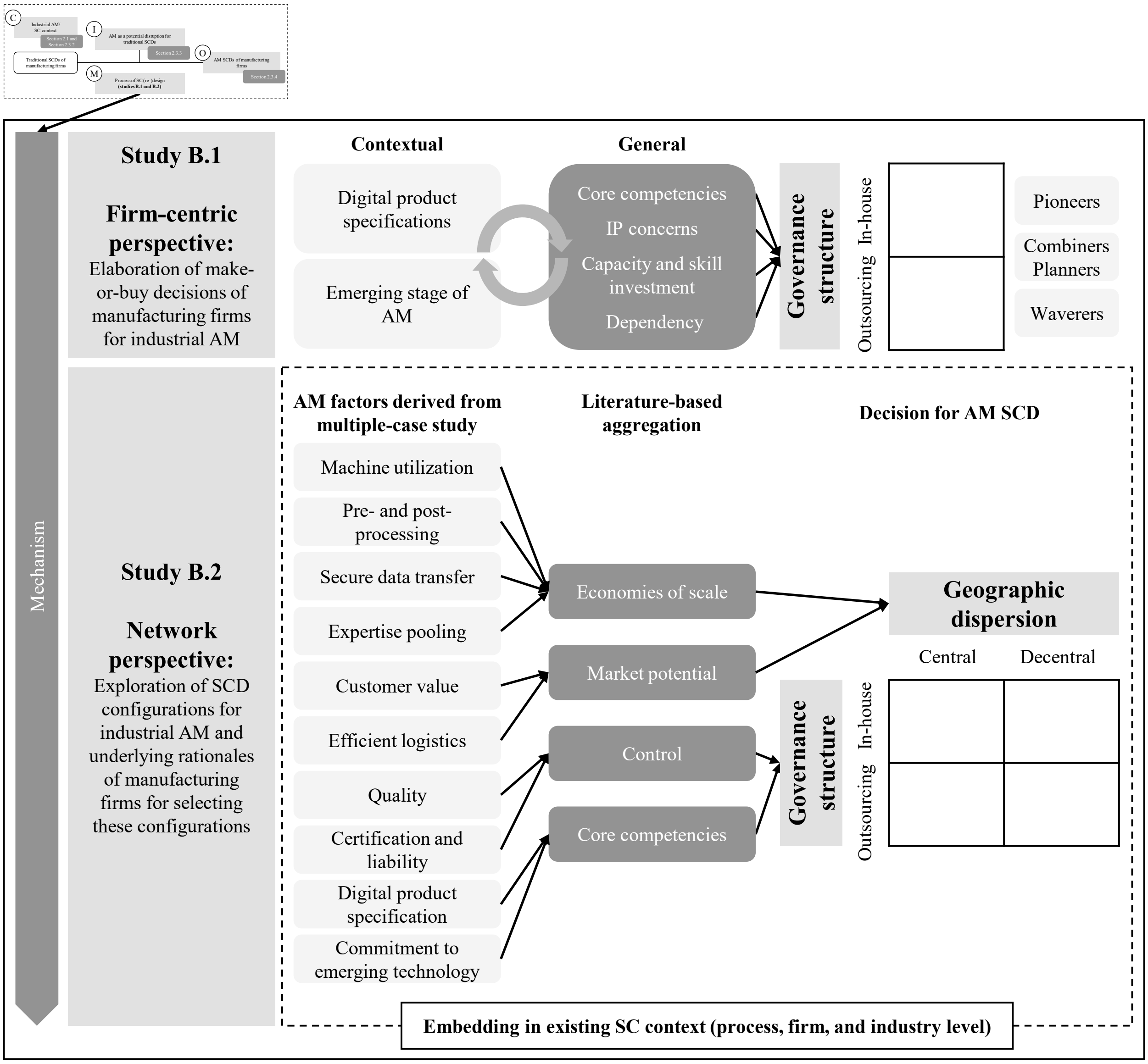


Figure 8-2: Summarized findings for the overarching research question RQB.

## 8.3 Overarching limitations and future research directions

This section summarizes the overarching research limitations of this thesis in Section 8.3.1 and, on this basis, derives broader directions for future research in Section 8.3.2. The limitations and future research directions are organized according to their conceptual and theoretical-methodological origins. This structure makes it possible to refer back to Chapter 2 and Chapter 3 multiple times, where the conceptual and theoretical-methodological frameworks of this thesis have been defined and described.

### 8.3.1 Research limitations

The research presented in this thesis comes with a number of limitations. From a conceptual perspective, they relate to the focus on a specific industry context and the assumptions made for approaching the AM business model development and SCD choice. Theoretical and methodological limitations arise from the selection of specific theoretical lenses, the concentration on qualitative research methodologies, and the applied data collection methods.

**Conceptual limitations**

An overarching limitation of this thesis lies in the conceptual focus on the **industrial AM context** (see Section 2.1), which is noticeable in all studies except study A.1. As voiced before, this focus is beneficial for deriving more context-specific results than the general expectations for the disruptive effect of AM that currently dominate the literature. However, theorizing in this specific context also entails that certain groups of actors (e.g., consumers) and industries (e.g., consumer goods) are not addressed in this thesis. Consequently, the results do not display the rationales of these actors and specifics of the resulting industries when it comes to the development of AM business models and the design of AM SCs (e.g., possibilities for user co-creation for consumer goods). To be more concrete, the different samples selected for the studies give a direct indication of which actors can take advantage of the derived findings. These are mostly large Western European LSPs and manufacturing firms from pioneering industries where challenging industrial AM has already started to create value. Addressed firms are characterized by their experience with industrial AM (and/or 3D printing in study A.1). Hence, they have initiated AM activities (LSPs) or started to incorporate AM into their operations (manufacturing firms). As often stated throughout the studies, SMEs are not sufficiently addressed in this thesis, mostly based on their lacking AM experience. Overall, the focus on the industrial AM context limits the generalizability of the theory-building and elaboration efforts in this thesis to other industries, groups of actors, and countries outside Western Europe.

Additional conceptual limitations result from the **assumptions** made for how the AM business model development of LSPs and SCD choice of manufacturing firms have been approached in this thesis. Selecting specific perspectives and foci for investigating the causal mechanisms behind the strategic decisions is necessary. However, it also naturally affects the derived outcomes. For example, the two studies on LSPs are broad, which is beneficial at the current very early stage of AM business model research for LSPs (see Section 2.2.4). The studies enable readers to gain a comprehensive overview of LSPs' reactions to AM and insights into a variety of generic AM business model configurations. However, such a broad view entails that specific reactions/AM activities and individual business model configurations are not deeply explored in this thesis. Exploring them would require a different, potentially more firm-centric methodological approach (e.g., a single-case study) than, for example, the extensive collection of data from websites in study A.1. In comparison, the literature base for the AM SCD choice is more advanced and already broader in itself since it is based on the two identified streams of literature from the OM and the SCM communities (see Section 2.3.4). As a result, studies B.1 and B.2 tackle more specific decision mechanics of manufacturing firms, the AM make-or-buy decision and the AM SCD choice. The extant literature provides for both decision mechanisms quite visionary outcomes that oftentimes cannot reflect the reality yet. Based on the discrepancies between literature-based visions and practice, the more in-depth studies B.1 and B.2 can also be viewed as starting points or initial theorization/theory elaboration. Polar governance structures as the outcomes of make-or-buy decisions (in-house versus outsourcing) and polar geographic dispersions (central versus decentral) are targeted for now. This initial focus reduces the complexity by basically simplifying the AM make-or-buy decision to two extremes and the AM SCD choice to a 2x2 matrix without considering intermediary decision outcomes, additional dimensions, and interrelated decisions for now. In addition, the concentration on the perspective of focal manufacturing firms reduces the decision complexity, even though the studies B.1 and B.2 consider the perspectives of other SC actors.

**Theoretical and methodological limitations**

From a theoretical perspective, first of all, the **selected theoretical lenses** influence and drive the results in certain directions. Based on the selected grand theories and MRTs/small-scale theories, the studies of this thesis navigate within specific constructs and terminologies and, thereby, may emphasize certain factors while others may be neglected. For example, the combination of TCE and the RBV has been applied to AM in study B.1 based on the proven explanatory power of the theories for make-or-buy decisions of traditional "analog" manufacturing technologies (see Section 3.1.2). However, it cannot be taken for granted that the selected theories can distill and appropriately weigh all specifics of digitally dominated transactions in AM.

Another limitation stems from the choice of predominately **qualitative research methodologies** (see Section 3.2.2). Qualitative research is mainly criticized for being too subjective and difficult to replicate. This criticism is based on the oftentimes quite "open-ended way" of qualitative research and the researcher's central role in the data collection and analysis. Hence, it is the researcher with personal preferences and beliefs that is decisive when it comes to which aspects to emphasize and include in the analysis. In addition, the process of data collection and analysis is oftentimes iterative, relatively unstructured, and not fully transparent for readers (Bell et al., 2019). Being aware of this criticism, this thesis provides detailed reasoning for the selected methodological approaches of the four studies in Chapter 3. In addition, it should be noted that the "open-ended way," creativity, triangulation of insights from different sources, and closeness of the researcher to the empirical context also turn into strengths of qualitative research. These characteristics distinguish qualitative research (Eisenhardt, 1989) and facilitate tackling the desired *how* and *why* questions in this thesis.

More specific limitations for the selected qualitative research methodologies concern the choice of units of data collection and the concrete **methods for data collection**. When evaluating the sampling process, all studies face the risk of potentially overemphasizing firms with successful AM experiences since such firms are probably more willing to share their experiences (e.g., in interviews and via publications on their websites). Finally, when considering data collection methods within the mostly qualitative research approaches in this thesis, it is striking that the studies are based on data triangulated from interviews, internal documents, and partly from a broad sample of websites (see Section 3.2.2). These data collection methods capture mostly retrospective views. For example, interviewees usually share their previous AM experiences. Moreover, it has been emphasized that websites provide "snapshots" of events at different points in time. As a result, the findings can mirror a specific stage in the industrialization of AM and firms' decisions and involvement at this point in time. These insights can be used for tentatively drawing a picture of projections for AM (e.g., of generic AM business model configurations for LSPs in study A.2). However, the ability to keep abreast with the rapid technological development and the high-velocity AM market is limited by the selected methods for data collection and would benefit from the increasing use of longitudinal data.

### 8.3.2 Paths for future research

The discussed limitations are suitable starting points for deriving opportunities for future research. With a focus on the conceptual scope of this thesis, obvious paths for future research lie in the transfer of the derived findings to other AM contexts. In addition, the developed understanding can be both deepened and broadened by adjusting the focus of future research. From a theoretical-methodological perspective, future research could benefit from other or additional theoretical lenses to distill further nuances in the findings. In this vein, this section provides multiple suggestions for grand theories and discusses their benefits in capturing specific aspects of AM. In addition, this section proposes how the findings of this thesis, for example, the derived propositions, could be operationalized in follow-up quantitative or pluralistic research approaches.

**Conceptual paths**

The pronounced focus on the industrial AM context contributes to building domain knowledge. To increase the level of differentiation, the derived findings can be compared and potentially enriched and extended with findings from **other contexts**. Also, the developed approaches (e.g., the consolidated factors influencing AM make-or-buy decisions or the matrix with dimensions and factors for investigating the AM SCD) and tools (e.g., the taxonomy of AM activities of LSPs) can be useful for other AM settings: Overall, the studies suggest the transfer and future application of the approaches to less regulated (consumer) industries, countries outside Western Europe, and firms with different characteristics (e.g., size and age). The findings could also form a basis for investigating how other actors react to the intervention of AM. For instance, the developed taxonomy could be adjusted for other service-oriented actors in the AM business ecosystem like AM service bureaus and AM software and platform providers. Analogously, the four AM SCD configurations of focal manufacturing firms could be extended from the perspective of AM-specific suppliers (e.g., AM service bureaus) and their industrial customers.

Furthermore, as explained in Section 8.3.1, the studies in this thesis can be viewed as starting points in multiple ways due to the currently scarce literature-based understanding of LSPs' positioning in AM and the rationales involved in manufacturing firms' strategic decisions: For part A (studies A.1 and A.2), future research can **narrow its focus** on specific AM activities/business models and their implications, for example, for LSPs' organizational structures, competitive dynamics within the AM business ecosystem, and compatibility with specific SCs. For part B (studies B.1 and B.2), the gained understanding of the rationales for polar decision outcomes of AM make-or-buy and AM SCD decisions could be **broadened** in future research. The findings set the ground for increasing the level of complexity by considering intermediary decision outcomes. In this sense, Section 2.3.4 has shown that AM is expected to foster the sharing and leasing of manufacturing infrastructure, and, as a result, intermediate governance structures like joint ventures and strategic alliances might emerge. Similarly, the literature-based expectations for the geographic dispersion suggest exploring "moderate" decentralization in hub AM SCDs and, based on the increased independence of tasks in AM, configurations with centralized control and different facets of decentralized AM activities. In addition, the interrelation of AM make-or-buy and SCD decisions with other decisions can be targeted in future research. For example, the AM make-or-buy decision may be an integral element of the AM sourcing process, and other interwoven decisions that can be explicitly considered are the demand specification, supplier selection, and contracting (Meyer et al., 2021). For the AM SCD choice, interrelated decisions may touch on the capacity for each manufacturing location, warehousing strategies, and distribution strategies.

**Theoretical and methodological paths**

Based on the outlined theoretical limitations, **additional theoretical lenses** that are also borrowed from other disciplines could be used to reveal further nuances in the findings. For example, the potentially disruptive characteristics and emerging stage of AM may benefit from theoretical lenses that are adopted from the fields of innovation management and technology acceptance and adoption (e.g., the diffusion theory, the technology acceptance model, and the technology-organization-environment framework). These theories could be suitable to explore not only how LSPs continue their AM business model development path but also how and why they leverage the technologies as users for their internal operations. To account for the digital dominance of AM and AM-based transactions, in particular the digitally encapsulated IP, the agency theory and property rights theory could be suitable theoretical lenses to elaborate how their arguments apply to digital AM. This could be a particularly fruitful path to extend and deepen the understanding of AM make-or-buy decisions. Moreover, when focusing on the inherently flexible nature of AM and the increasing commoditization of manufacturing equipment, the relational view may become a suitable lens once the sharing of decentralized manufacturing infrastructure (e.g., regional AM "supercenters") starts to create opportunities for leasing, increased cooperation, and self-services of industrial customers (Sasson & Johnson, 2016). By applying the relational view for such SCD configurations, inter-organizational competitive advantages that lie in dyadic relationships or networks could be explored for AM in comparison to traditional manufacturing technologies.

Moreover, from a methodological perspective, the dominant qualitative research approaches in this thesis suggest both future research that continues to use **qualitative methodologies and more pluralistic approaches** that are based on methodological triangulation. This thesis assesses qualitative research as independent and powerful in itself. In this vein, subsequent qualitative research (e.g., case study research) could, for example, be suitable for gaining in-depth insights into specific AM business models for LSPs. In addition, by following Eisenhardt (1989), even though she takes a positivist position, this thesis supports that qualitative research methodologies, particularly case study research, can be directed toward the development of testable hypotheses. In this thesis, studies A.1 and B.1 both suggest a set of propositions that could potentially be formalized in follow-up quantitative research. For example, the derived six profiles of responses of LSPs to AM (study A.1) and resulting business model dynamics could be tested in a large-scale survey. Additionally, the propositions of study B.1 could be used for setting up a game-theoretical model for the outsourcing of AM based on realistic assumptions. As proposed by Flynn et al. (1990) and McCutcheon and Meredith (1993), qualitative research is a prerequisite for analytical modeling and testing in a controlled environment. In this vein, the real-world insights gained from the studies could foster additional pluralistic methodological choices, as evident in the mixed-methods approach in study A.1, and, thereby, increase the understanding for the specifics of AM.

Finally, it is reflected throughout the studies presented in this thesis that what applies to AM does not necessarily apply only to AM. In this sense, it has been repeatedly suggested that what can be observed for AM may be relevant for technologies with similar digital and/or emerging traits. Hence, this thesis suggests broader research to build theory and elaborate on the applicability of existing theory in the era of digital, potentially shorter, and decentralized SCs. The configurations proposed in this thesis for AM – for generic business models and SCDs – are suitable and valuable structures to meet firms' competitive strategies at specific points in their AM implementation. New configurations are likely to emerge that capture the full potential of AM to enable decentralized manufacturing and increased outsourcing to local partners. This thesis encourages future research to continue to explore firms' decision patterns, manifested in configurations that create a fit between firms' structures, strategies, and the maturing industrial AM context, and draw comparisons to other digitally dominated technologies.

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