Tampere University

TONI LUOMARANTA

Managing the Adoption of Additive Manufacturing

A systemic manufacturing innovation and sustainability perspective

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ACADEMIC DISSERTATION
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Responsible supervisor and Custos	Professor Miia Martinsuo Tampere University Finland	
Pre-examiners	Professor Harm-Jan Steenhuis Hawaii Pacific University United States	Professor Fabio Nonino Sapienza University of Rome Italy
Opponent	Professor Anna Öhrwall Rönnbäck Luleå University of Technology Sweden	

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Innovation as a thing and action; technology as inseparable from human values and purposes; and technological innovation as complex interaction of people, scientific concepts, aspirations, and consequences. The more we learn about the components of these processes, the more we realize that the whole remains beyond our grasp. But after all, human efficacy is always at the margin; whatever we can find out that helps us avoid being whipsawed by our own systems is better than nothing.

Eveland and Tornatzky, 1990, p. 50

PREFACE AND ACKNOWLEDGEMENTS

From early on, when starting as a doctoral researcher, I had the gut feeling that new manufacturing technology innovation of additive manufacturing was intertwined with many other perspectives that make it useful for the society. Firstly, additive manufacturing is a innovation that not only contributes to incremental innovation to enhance the Schumpeterian throughput of company, but is also more and more tied into what is being manufactured with the technology. Therefore, product innovation and process innovations become closely tied to the success of new technology. Also, the manufacturing technology is constantly developing, opening possibilities for further innovations in the product side of the technology.

Secondly, taking a step outside of the purely technological view, the product and process innovations are again intertwined with the organizational processes on perceiving and adopting new technology. This comes alongside with the innovation activities that organizations need to go through, and how inter-organizational collaboration is both sought and organized, and how the external stakeholders see and influence the process.

To have a change of writing a doctoral dissertation was a wonderful opportunity for me. And what a journey has it been to understand myself and maybe even the surrounding world a tiny bit more. The amount of work this doctoral dissertation required was enormous. Luckily, I was not alone during this research and writing process and I would like to thank everyone involved.

First of all, I want to express my deepest gratitude for my supervisor Professor Miia Martinsuo. You have been the greatest enabler for this dissertation to even start it, let alone to get it ready. Thank you for hiring me as a project research for Välkky-project, that I see as the starting point of my doctoral studies. Thank you for trusting me even further and taking me along to the demanding EU Horizon2020 IAMRRI-project. These projects allowed me to see the research work outside my dissertation, but also enabled and motivated me to carry on my own dissertation. Thank you for the support, insights and working with me.

Next, I would like to express my gratitude for the thorough, critical and supportive pre-examiners' statements of Professor Harm-Jan Steenhuis from Hawaii Pacific University and Professor Fabio Nonino from Sapienza University of Rome for investing the time in evaluating my work. The statements encouraged me to find a few more places to further improve my dissertation. I am honored to have Professor Anna Öhrwall Rönnbäck as my opponent. I would also like to thank Professor Saku Mäkinen for conducting internal examination for my dissertation before pre-examination and giving constructive comments on how to improve my manuscript. Furthermore, I would like to thank the anonymous peer-reviewers of the journal and conference articles, and the editors and editorial boards of the journals and conference that published my research.

Dear members of the CROPS research team throughout the years, thank you for the great support and sharing the journey, Matias, Eija, Lauri, Beheste, Markus, Prasanna, Sebastian, and Tuomas. I want to also thank my other colleagues at the university during the doctoral journey, Natalia, Lauri, Johanna, Milla, Valtteri, Jussi and Vesa. Thank you, Ilona, for the years as your co-teacher and the support and responsibilities you gave me. Thank you Santtu, Teemu, Tuomas and Leena for the small discussions we had that helped me to carry on.

I want to thank all the colleagues from Välkky-project and IAMRRI-project. I want to acknowledge the financial role of these two projects Välkky (funding from European Commission European Regional Development Fund) and IAMRRI (funding from European Union Horizon2020 program) for my dissertation. I also acknowledge the financial support from Tekniikan edistamissäätiö (The Finnish Foundation for Technology Promotion), Tampereen kaupungin Tiederahasto (Tampere city Science fund) and Yrjö ja Senja Koivunen foundation.

I also acknowledge the financial support from Erasmus+ program and Metallinjalostajien rahasto (Steel and Metal Producers' Fund under the Technology Industries of Finland Centennial Foundation) for enabling me the lengthy research visits to University of Economics in Bratislava, TU Wien and Fraunhofer Austria. I want to thank Klaudia, Radka and Arko for making the research visits possible and interesting. The research visits and the change of rhythm of life due to them allowed me to really focus on writing and finishing this doctoral dissertation.

I want to thank my dear friends Ilkka, Olli, Joona, Jesse and Hans. You not only share the passions of my life and help me find joy in life whether then in water, on snow or at the workshop, but I had the privilege to wonder the world together with you. And Mark, those discussion we had in countless car drives to surf or to snowboard and sharing the burden of writing doctoral dissertation have been invaluable.

I want to thank my dear friends Johanna, Ilmari, Noomi, Nelli and Maiju for the many evenings and trips, all the discussion we had that helped me to see the complex

society outside the industrial engineering and management discipline box. Those discussions have greatly influenced my thinking.

I would not be here without the support and upbringing of my parents Anne-Maj and Timo. Thank you, mum and dad, for being there for me! I am so grateful to have the best Siblings&Co, Anette, Tuukka and Päivyt to share the life with. I would also like to thank my grandparents for giving me inspiration and perspective for life. Furthermore, I would like to thank my whole family-in-law Reiniö for all the support and time spent together throughout the years.

Finally, my love, my wife Noora thank you for sharing this life with me. Thank you supporting me, rejoicing with me, comforting and cheering me up, and arranging wonderful adventures together with me during these years.

Toni Luomaranta
August 2022
Tampere, Finland

ABSTRACT

Successful production transformation of manufacturing organizations, driven by technological developments, is increasingly important for the economy and society, as well as for a sustainability transition. Advanced manufacturing technologies not only enhance current production methods but also enable the creation of new manufacturing processes and the manufacturing of new types of products. The adoption of these kinds of systemic manufacturing technologies presents a novel research need and positions the topic of this dissertation in technology and innovation studies from a sociotechnical perspective. Additive manufacturing (AM) is one of the prominent advanced manufacturing technologies, where the expected benefits are greater than the drawbacks, and is the technological context of this dissertation.

The diffusion of AM on an industrial scale is not a simple implementation task of introducing a new type of machine into the operations of an organization, but is a complex adoption process that requires supporting and complementary innovations in multiple places in the value chain as well as interorganizational collaboration to share the knowledge of pioneers. As the diffusion of prominent new manufacturing technology has not been as expected, research is needed to study the adoption of AM from multiple perspectives to generate new theoretical knowledge that simultaneously supports the adoption of AM in practice.

The aim of this dissertation is to provide new knowledge on ways of managing the adoption of AM as an advanced manufacturing technology innovation in interorganizational networks. Second, this dissertation aims to provide new knowledge on the consideration of sustainability perspectives during AM adoption and subsequent AM innovations. Third, the aim is to aggregate the findings and provide new context-specific knowledge from AM (as an advanced manufacturing technology innovation) into the literature of technology adoption. The aim of the dissertation is approached through one main research question and two sub-questions. The main research question is: How, through what kind of an innovation adoption process, do organizations adopt AM? The sub-questions are: How do organizations manage the adoption of AM in their interorganizational networks, and how do organizations address sustainability in AM innovations?

This article-based dissertation utilizes a sequential research design and includes four original articles, of which three are published in scientific peer-reviewed journals and one is published in peer-reviewed conference proceedings. The empirical and qualitative research data were collected in various combinations of interviews, workshops, and a qualitative survey, depending on the individual study in this article compilation. The data were collected from manufacturing companies and other related organizations in relevant networks in the fields of machine building, the process technology industry, and biomedical applications. This dissertation studied AM adoption from the interorganizational level of analysis, supported by the organizational level of analysis.

The adoption of AM is a complex process of systemic manufacturing innovation adoption, where the adoption of new technology itself is not meaningful, but the goods manufactured with AM define whether the technology is attractive to the organization's needs. Furthermore, the adoption of AM might take place throughout the value chain, and the added value has to be carefully envisioned through value-driven design.

This dissertation thus contributes to the technology innovation adoption theory by showing that AM adoption, as a systemic manufacturing innovation, requires complementary innovations. These complementary innovations are found in the forms of supply chain innovations, process innovations, and new product innovations. Without the added value in the aforementioned innovations, the technology is not worth adopting. Interorganizational collaboration through innovation projects is a possible way to overcome adoption barriers and ease the knowledge sharing from pioneers to adopters during AM adoption-related innovation projects. Sustainability considerations can be included in the value-driven design to support the sustainability outcomes of new AM innovations. Stakeholders are shown to be relevant to enhancing both adoption success and sustainability, as they provide knowledge and support to guide AM innovation for the needs of society.

This dissertation further contributes to the practice of AM adoption specifically by showing how the complex phenomenon of systemic manufacturing innovation can be treated in a modular way and provides examples of potential adoption challenges and barriers, supply chain level issues, stakeholder level issues, adoption as an innovation process, and how all of these can be used to inform practitioners when introducing AM into networks.

TIIVISTELMÄ

Teknologisen kehityksen ajamana tuotanto-organisaatioiden onnistunut transformaatio eli syvämuutos on yhä tärkeämpää taloudelle ja yhteiskunnalle sekä kestävän kehityksen siirtymälle. Edistyneet valmistustekniikat paitsi tehostavat nykyisiä tuotantomenetelmiä, myös mahdollistavat uusien valmistusprosessien kehittämisen ja uudentyyppisten tuotteiden valmistuksen. Tällaisten systeemisten valmistusteknologioiden käyttöönotto tarjoaa uudenlaisen tutkimustarpeen ja asemoi tämän väitöskirjan aiheen teknologia- ja innovaatiotutkimukseen sosioteknisestä näkökulmasta. Lisäävä valmistus (englanniksi: additive manufacturing, AM) on yksi merkittävimmistä edistyneistä valmistusteknologioista, jossa odotetut hyödyt ovat haittoja suuremmat, ja on tämän väitöskirjan teknologinen konteksti.

Lisäävän valmistuksen leviäminen käyttöön teollisessa mittakaavassa ei ole vain yksinkertainen uudenlaisen koneen ottaminen osaksi organisaation toimintaa, vaan monimutkainen omaksumisen prosessi, joka vaatii tukevia ja täydentäviä innovaatioita useissa arvoketjun paikoissa sekä organisaatioiden välistä yhteistyötä pioneerien tiedon jakamiseksi. Koska tämän teknologisilta mahdollisuuksiltaan merkittävän uuden valmistusteknologian leviäminen ei ole tapahtunut odotetusti, tarvitaan tutkimusta lisäävän valmistuksen omaksumisesta useista näkökulmista, jotta saadaan aikaan uutta teoreettista tietoa, joka samanaikaisesti tukee teknologian käyttöönottoa tuotanto-organisaatioissa.

Tämän väitöskirjan tavoitteena on tarjota uutta tietoa tavoista johtaa lisäävän valmistuksen omaksumista eli edistyneen valmistusteknologian innovaation käyttöönottoa organisaatioiden välisissä verkostoissa. Toiseksi tämän väitöskirjan tavoitteena on tarjota uutta tietoa kestävän kehityksen näkökulmien huomioon ottamisesta lisäävän valmistuksen omaksumisen, käyttöönoton ja sitä seuraavien innovaatioiden aikana. Kolmanneksi tavoitteena on koota havainnot ja tarjota uutta kontekstikohtaista tietoa lisäävästä valmistuksesta (edistyneenä valmistusteknologian innovaationa) teknologian omaksumisen tieteelliseen kirjallisuuteen. Väitöskirjan tavoitetta lähestytään yhden päätutkimuskysymyksen sekä kahden alakysymyksen kautta. Päätutkimuskysymys on: Miten ja minkälaisen innovaatioiden omaksumisprosessin kautta organisaatiot ottavat käyttöön lisäävän valmistuksen teknologiaa? Alakysymykset ovat: Miten organisaatiot johtavat lisäävän valmistuksen

omaksumista ja käyttöönottoa organisaatioiden välisissä verkostoissaan ja miten organisaatiot käsittelevät kestävää kehitystä lisäävän valmistuksen innovaatioissa?

Tämä artikkelipohjainen väitöskirja on toteutettu peräkkäistutkimuksena ja sisältää neljä alkuperäistä tutkimusartikkelia, joista kolme on julkaistu tieteellisissä vertaisarvioiduissa aikakauslehdissä ja yksi on julkaistu vertaisarvioidussa konferenssijulkaisussa. Empiirinen laadullinen tutkimusaineisto kerättiin hyödyntäen haastatteluja, työpajoja ja laadullista kyselyä ja yhdistelemällä niitä riippuen yksittäisestä tutkimuksesta tässä artikkeliväitöskirjassa. Aineisto kerättiin koneenrakennuksen, prosessiteknologiateollisuuden ja biolääketieteen teollisuudenalojen verkostoissa olevilta valmistavan teollisuuden yrityksiltä ja muilta näihin aloihin liittyviltä organisaatioilta. Tässä väitöskirjassa tutkittiin lisäävän valmistusteknologian omaksumista organisaatioiden väliseltä analyysin tasolta ja sitä tuettiin organisaatiotason analyysillä.

Lisäävän valmistuksen käyttöönotto on monimutkainen systeemisen tuotantoinnovaatioiden omaksumisen prosessi, jossa uuden teknologian omaksuminen itsessään ei ole mielekästä, vaan tällä uudella teknologialla valmistetut tuotteet määrittelevät, onko teknologia houkutteleva organisaation tarpeisiin. Lisäksi lisäävän valmistuksen omaksumisen voi katsoa tapahtuvan läpi koko arvoketjun, ja teknologian tuoma lisäarvo on harkittava ja suunniteltava huolellisesti arvolähtöisen suunnittelun avulla.

Tämä väitöskirja myötävaikuttaa siten teknologiainnovaatioiden omaksumisen teoriaan osoittamalla, että lisäävän valmistuksen omaksuminen systeemisenä valmistusinnovaationa vaatii toisiaan täydentäviä innovaatioita usealla eri alueella. Näitä täydentäviä innovaatioita löytyy toimitusketjuinnovaatioiden, prosessi-innovaatioiden ja uusien tuoteinnovaatioiden muodoissa. Ilman edellä mainittujen innovaatioiden tuomaa lisäarvoa teknologiaa ei välttämättä kannata ottaa käyttöön. Organisaatioiden välinen yhteistyö innovaatioprojektien kautta on mahdollinen tapa ylittää omaksumisen esteet ja helpottaa tiedon jakamista pioneereilta omaksujille innovaatioprojektien aikana. Kestävyysnäkökulmat voidaan sisällyttää arvolähtöiseen suunnitteluun tukemaan uusien lisäävän valmistuksen sekä täydentävien innovaatioiden kestävää kehityssuuntaa. Sidosryhmien osoitetaan olevan merkityksellisiä sekä omaksumisen onnistumisen että kestävyyden edistämisessä. Ne tarjoavat tietoa ja tukea, jolla lisäävän valmistuksen innovaatioita voidaan ohjata yhteiskunnan tarpeisiin.

Tämä väitöskirja edistää edelleen lisäävän valmistuksen teknologian omaksumista osoittamalla, kuinka monimutkaista systeemistä valmistusinnovaatiota voidaan käsitellä modulaarisesti, tarjoamalla esimerkkejä mahdollisista omaksumisen haasteista ja esteistä, toimitusketjun ongelmista, sidosryhmätason ongelmista, hyväksymisestä osaksi innovaatioprosessia ja kuinka näitä kaikkia voidaan käyttää hyödyksi tai haasteet ratkaista, kun lisäävä valmistus omaksutaan ja otetaan käyttöön.

CONTENTS

ORIGINAL PUBLICATIONS

Publication I	Martinsuo, M., & Luomaranta, T. (2018). Adopting additive manufacturing in SMEs: Exploring the challenges and solutions. *Journal of Manufacturing Technology Management*, 29(6), 937–957.
Publication II	Luomaranta, T., & Martinsuo, M. (2020). Supply chain innovations for additive manufacturing. *International Journal of Physical Distribution & Logistics Management*, 50(1), 54–79.
Publication III	Luomaranta, T. (2020). Additive manufacturing innovations: Stakeholders' influence in enhancing sustainability and responsibility. In *Proceedings of the XXXI ISPIM (International Society for Professional Innovation Management) Innovation Conference*, Innovating in Times of Crisis, 7–10 June, 2020, p. 1–18.
Publication IV	Luomaranta, T., & Martinsuo, M. (2022). Additive manufacturing value chain adoption. *Journal of Manufacturing Technology Management,* 33(9), 40–60.

AUTHOR'S CONTRIBUTION TO CO-AUTHORED PUBLICATIONS

In publication I, I generated the idea for the article with the co-author, Professor Miia Martinsuo, who was the corresponding author. I reviewed the literature and wrote the first version of the literature review, which was then elaborated upon with the co-author. I arranged the interviews and collected the interview data. I analyzed the interview data and wrote the first version of the findings, which was then rearranged by and elaborated with the coauthor. The first version of the discussion and conclusions were written jointly with the co-author, and the full paper was further developed jointly. Professor Martinsuo led the revision process, the peer-review feedback from the journal was discussed together, and the revisions of the article were written with the coauthor.

In publication II, I generated the idea for the article and was the corresponding author. I reviewed the literature and wrote the first version of the literature review, which was then elaborated on with the coauthor, Professor Miia Martinsuo. I arranged the interviews and collected the interview data. I analyzed the interview data and wrote the first version of the findings, discussion, and conclusions, and these were developed further with the coauthor. I presented the work-in-progress version of this article at the European Operations Management Association (EurOMA 2018) conference, and the feedback was used when further developing the paper for a journal. The peer review feedback from the journal was discussed together. I wrote the first revision versions of the article, and those were then elaborated with the coauthor.

In publication III, I was the sole author. A preliminary version of the article idea was written with my supervisor, Professor Miia Martinsuo, and I presented it at the EurOMA 2019 conference and collected feedback. For the final published version, I refocused the scope and rewrote the entire article. I presented the final article at the virtual International Society for Professional Innovation Management (ISPIM 2020) conference.

In publication IV, I generated the idea for the article and was the corresponding author. I reviewed the literature and wrote the first version of the literature review, which was then elaborated on with the coauthor, Professor Miia Martinsuo. I arranged the interviews and collected the interview data. I analyzed the interview data and wrote the findings and the first version of the discussion and conclusions. All sections of the article were elaborated upon with the coauthor. An early work-in-progress version of this article was included in the proceedings of the EurOMA 2021 conference. After the conference, a full paper was developed for the journal. The peer feedback was discussed together. I wrote the first version of the revisions of the article, and those were then elaborated together with the coauthor.

1 INTRODUCTION

1.1 Background

The successful production transformation of manufacturing companies is increasingly important for economic growth (Holmström et al., 2021). Technological developments have been influential in driving the changes in production transformation (Rehnberg & Ponte, 2018), and the digitalization of industrial value chains accompanied by new digital manufacturing technologies such as additive manufacturing (AM) is a current example of such technologies (Baldwin, 2016). On a company level, advanced manufacturing technologies contribute to competitive capabilities and thus potentially to the performance of manufacturing organizations in capitalist economies (Skinner, 1996; Small & Yasin, 1997; Sun & Hong, 2002; Tracey et al., 1999). In the concluding remarks from the Uptake of Advanced Manufacturing panel discussion during EU Industry Days (2022), the panel moderator conclusion well emphasis the importance of this topic:

> Adoption of advanced manufacturing is the key for enhancing the welfare, the competitiveness and role of Europe as well as sustainability of manufacturing sector. To support adoption—collaboration helps, sharing knowledge helps, and eventually the whole supply chain has to be taken into consideration.
>
> *(EU industry days 2022, concluding remarks from Uptake of Advanced Manufacturing, panel discussion)*

Additive manufacturing has begun to take a foothold in industrial production in recent years, and the first major metal components manufactured by AM for end-use were introduced to the public in 2016. It has been argued that additive manufacturing technology will trigger and drive the fourth industrial revolution (Schwab, 2015), and it thus has the potential to fundamentally change the industry to a more tailor-made and sustainable way of acting. Additive manufacturing has already been identified to promote sustainable development and production through component and material life cycles (Ford & Despeisse, 2016), and the importance of

AM in industry has also been taken into account at the European Commission level by working with the AM strategy in early 2017 (CECIMO, 2017). However, there is still a need to understand the adoption of AM technologies, as many companies hesitate to select and adopt AM due to uncertainty and a lack of knowledge about AM technologies and their usage (Sobota et al., 2021).

In this dissertation, adoption of new manufacturing technology is defined as the phenomenon of how manufacturing technology innovation comes to be used in certain ways and for certain purposes (Preece, 1991), and it therefore includes adoption decision making and initial implementation, as defined by Rogers (1962, 2003) and Tornatzky and Fleischer (1990). The phases of the innovation process preceding adoption (awareness/knowledge gathering, persuasion, matching/selection) and the follow-up (routinization of adopted technology) (Rogers, 1962, 2003; Tornatzky and Fleischer, 1990), are not under focus in this dissertation.

The AM industry is currently emerging (Ortt, 2016, 2017). This means that the adoption of the technology innovation context is in the early phase, which is an important research area, as adoption is a complex process that provides a range of beneficial possibilities (Preece, 1991), ranging from competitive advantages (Tracey et al., 1999) to sustainability outcomes (Jay & Gerand, 2015). Thus, adoption is critical not just for understanding how new technology has been adopted and used in a particular organization but also why it has been adopted and used, which is associated with what value is generated (Preece, 1991). Earlier research has noted that the adoption of advanced manufacturing technologies (which AM represents) may impose a systemic change on organizations and networks (Tyre, 1991). This means changes to every aspect of how production functions, and the adoption process resembles a research project (Tyre, 1991). Furthermore, if technology innovation is systemic in nature, it implies the need for complementary innovations to become feasible (Takey and Carvalho, 2016), which potentially adds to the complexity of adoption.

In addition to the adoption of technology within one company, the relevance of company networks is recognized in the adoption process in general (Arvanitis & Hollenstein, 2001; Linton, 2002), and in the context of AM (Oettmeier & Hofmann, 2016; Rylands et al., 2016; Stentoft et al., 2021). This is because innovation adoption is mainly an information processing activity among organizations (Talukder, 2014), and organizations can facilitate the diffusion of information about technological innovation in their networks (Frambach & Schillewaert, 2002). Besides knowledge sharing, interorganizational collaboration allows organizations to collaborate and build on the strengths of other firms and thus legitimize the new technology, add value, and support adoption (Arlbjørn et al., 2011; Chesbrough, 2003; Garud et al., 2013; Van de Ven, 2004), which is potentially important for a technology such as AM.

Since the adoption (and subsequent use) of new technologies (innovations) enables novel value generation (Preece, 1991; Schumpeter, 1934), it also allows value generation from a sustainability perspective (Jay & Gerand, 2015), and this is especially emphasized with respect to advanced manufacturing technology innovations (CECIMO, 2017, 2019). Sustainability is important because innovations are arguably no longer valuable regardless of the ecological consequences. Research is needed to generate knowledge about how sustainability and economies can benefit each other through innovation and the adoption of advanced manufacturing technology innovations such as AM. To conclude, Figure 1 shows the key concepts and positioning of this study, which are technology adoption, interorganizational networks, and sustainability in the specific technology innovation context of AM.

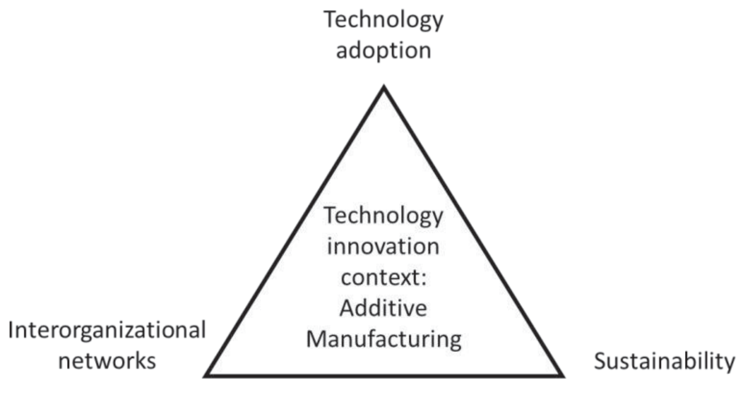

Figure 1. Positioning of this doctoral dissertation

The purpose of this dissertation is to study the adoption of AM, and more specifically, how the adoption process unfolds in interorganizational networks, how the new supply and value chains emerge, and what kinds of stakeholders take part in this. This dissertation is carried out as an article compilation. The first three articles of this doctoral dissertation employ an explorative research approach to study phenomena that have not yet been widely researched. The fourth article is a case study with purpose to create a deeper understanding from the phenomenon of AM adoption.

1.2 Goals, research questions, and scope delimitations

The rationale of this study is that AM is a new advanced manufacturing technology innovation, and its benefits are expected to be greater than its drawbacks for business and sustainability. For these benefits to be realized, it is of high importance to find ways to overcome obstacles and challenges to enable companies to adopt new manufacturing technology (Preece, 1991). The added value of AM needs to be studied more closely throughout the entire industrial manufacturing value chain. It is relevant to study how interorganizational networks for increasing AM production will be shaped in the future and how organizations will benefit from AM technology. Finally, it is worth exploring how sustainable this development is and how the principles of sustainable development could be included in the early phase of the new manufacturing technology.

This dissertation studies the adoption of AM in interorganizational settings. The aim of this dissertation is to provide new knowledge on ways of managing the adoption of AM as an advanced manufacturing technology innovation in organizational networks. Second, this dissertation aims to provide new knowledge on the consideration of sustainability perspectives during AM adoption and subsequent AM innovations. The third aim is to aggregate the findings and provide new context-specific knowledge from AM (as an advanced manufacturing technology innovation) into the literatures on technology adoption.

The level of analysis and the focus are purposely on interorganizational networks, although organizational-level analysis is used to support network-level analysis. The rationale is that new technology can be more useful when diffused widely to manufacturing networks. Networks, rather than organizational levels of analysis, better reflect the reality that technology adopters encounter (Linton, 2002). Although the adoption of AM can take place within a single company on some occasions, for the sake of wider relevance of this dissertation, the focus is on the network level. In this way, the findings of this dissertation are estimated to be more widely usable than focusing on single companies alone. The aims of this dissertation are approached through one main research question and two sub-questions:

Main research question:

- How, through what kind of an innovation adoption process, do organizations adopt AM?

Sub-question 1:

- How do organizations manage the adoption of AM in their interorganizational networks?

Sub-question 2:

- How do organizations address sustainability in AM innovations?

The AM context offers an opportunity to study the early phase of specific advanced manufacturing technology innovation adoption in the field, as AM applications and solutions are still in a very early stage. The early phase of AM offers a setting where multiple different organizations are active in the AM field. From the technology perspective, attention is paid specifically to metal and ceramic AM and related services and their adoption. Polymer AM technology adoption is not empirically studied, but earlier research is examined at the general level. The technological solutions of AM machines and their development are excluded from this study.

1.3 Research process and dissertation structure

This doctoral research is conducted as a compilation dissertation and includes three journal articles and one conference proceedings article. Table 1 summarizes how each article contributed to the research questions of this dissertation. The original articles are included in the dissertation's printed edition in the appendix.

Table 1. Articles and their contribution to research questions (X = major contribution, O = minor contribution)

Research questions	Article I	Article II	Article III	Article IV
Main research question: How, through what kind of an innovation adoption process, do organizations adopt AM?	X	X	X	X
Sub-question 1: How do organizations manage the adoption of additive manufacturing in their interorganizational networks?	X	X	O	X
Sub-question 2: How do organizations address sustainability in AM innovations?			X	X

Each article is an empirical study and is qualitative in nature. The empirical data were collected in various stages, and the articles were written sequentially. These sequential stages are explained in detail in section 3, and below is a brief discussion of the articles and the overall research process.

From 2017 to 2018, I worked on the research project "Demanding digital manufacturing" (Vaativa digitalinen valmistus/Välkky-projekti, funded by the European Regional Development Fund, ERDF), which was a workshop-based research project aiming to promote the adoption of metallic AM among local small and medium-sized enterprises. The empirical interview and workshop data for Articles I and II were collected during this project. The interview dataset for Articles I and II include some of the same organizations and informants. A thematic interview outline was developed, and data from around half of the themes were utilized in the analysis in Article I. This dataset includes only small and medium-sized enterprises (SMEs). The unanalyzed themes were used in the analysis in Article II, and another interview round was organized to complement the views of SMEs with views from large corporations.

The purpose of Article I was to explore the perspectives of SMEs on the AM adoption. The aim was to generate new insight and knowledge on the challenges experienced before or during the adoption of AM and the actions taken to overcome these challenges. The purpose of Article II was to map the AM-related supply chain process and explore supply chain innovations that are triggered by the introduction of AM to the supply chain. The aim was to generate new insight and knowledge about how different companies in different supply chain positions view the adoption of AM into their supply chains and the supply chain innovations needed to start leveraging the benefits of AM comprehensively.

From 2018 to 2021, I worked on the research project I AM RRI (Webs of Innovation and value chains of Additive Manufacturing, under the consideration of Responsible Research and Innovation), funded by the European Commission's Horizon2020 program. The purpose of the I AM RRI project was to study the innovation value chains of AM from the perspective of responsible research and innovation. The empirical workshop and qualitative survey data were collected during this project in a European context. The purpose of Article III was first to identify the relevant primary stakeholders (i.e., organizations in the supply chain) and secondary stakeholders involved in AM. Second, the influence of secondary stakeholders was analyzed in relation to the AM innovations. The aim was to generate a new understanding about how stakeholders' involvement influences the success and sustainability (and responsibility) of AM innovations.

For Article IV, a case study setting was established with networks of companies that had participated in a successful AM innovation project. Two different projects (the second project having two sub-projects) were studied with two focal organizations together with the collaborating organizations in the projects. The purpose of Article IV was to study successful AM adoption cases about how the process of adoption unfolded, what kinds of companies were involved in the projects, and what kinds of changes took place at the supply chain level. The aim was to understand how and why certain companies adopt AM in their value chain even though they do not directly invest in AM machines.

The next chapter introduces this dissertation's theoretical underpinnings. These are needed to further understand and theorize the adoption of systemic manufacturing innovations. The theoretical concepts presented in the second chapter are advanced manufacturing technology innovation, technology innovation adoption, interorganizational collaboration, and the sustainability of manufacturing technology innovations. Then, AM as an advanced manufacturing technology and this dissertation's main context is introduced. This is followed by a review of previous literature about AM adoption and supply chain implications, as well as the sustainability aspects of manufacturing innovations together with stakeholder influences.

This dissertation's methodological setting is discussed in the third chapter, which includes the philosophy of science orientation (constructive-interpretative and pragmatic), research design (qualitative explorative and case-study), data collection (interviewing, workshopping, and qualitative open-ended survey), and data analysis (thematic inductive and abductive analysis).

The fourth chapter highlights the important findings of the original articles. Article I explores the challenges and barriers of AM adoption and shows that different types of organizations experience these differently. The main barriers identified are the need to involve supply chain in AM adoption and recognize suitable applications (i.e., product innovations). Article II reveals that different types of organizations collaborate in the emergent AM supply chain. Both expected and needed changes at the supply chain level take place simultaneously with AM adoption. Article III shows that outside the supply chain, there are organizations (secondary stakeholders) that seek to or may (when actively involved) influence the success of AM product innovations and AM adoption. These secondary stakeholders offer support or restrictions regarding the sustainability (and responsibility) of AM innovations. Article IV presents how the AM adoption process proceeded in two cases through AM innovation projects and reveals that interorganizational collaboration provided a means to overcome the barriers of supply chain restructuring and application recognition. Eventually, it was concluded that the AM adoption was actually the adoption of the AM value chain, and this illustrates the systemic nature of AM adoption.

The fifth chapter considers the dissertation's overall contributions in light of the previous literature. First, the findings of AM adoption are discussed. This provides new knowledge by binding together the adoption barriers, the multiple different organizations involved and the interorganizational collaboration between them, and complementary innovations in supply chains as well as product innovations as integral parts of AM adoption management. Second, the findings regarding AM innovations from the perspective of sustainability (and responsibility) are discussed. This shows that the adoption of AM provides the potential to address sustainability (and responsibility) through innovation processes as part of AM adoption. Third, the findings are aggregated from the AM context into the level of systemic manufacturing innovation adoption. This discussion suggests that two main findings of interorganizational collaboration and complementary innovations can elaborate technology innovation adoption theories in the specific context of the emergent industrial field and systemic manufacturing innovation. The sixth chapter of the dissertation summarizes the study's scientific contributions and managerial implications and evaluates the dissertation research.

2 THEORETICAL BACKGROUND

2.1 Key concepts

This chapter presents the key theoretical concepts and definitions that are needed to understand the phenomenon under study. First, advanced manufacturing technologies are explained, starting from the roots of what a technology is. Then, the adoption of technologies is briefly presented, followed by explanations of interorganizational collaboration, stakeholders, supply chains, and value chains, as they form another important angle for this dissertation. Finally, the concepts of sustainability in manufacturing technology innovations are explained.

2.1.1 Advanced manufacturing technology innovations

This dissertation is essentially about advanced manufacturing technology and its adoption. To break down advanced manufacturing technology adoption, there is first a need to understand what "technology" is. Technology has been defined as "a system created by humans that uses knowledge and organization to produce objects and techniques for the attainment of specific goals" (Volti 2009, p. 6), or "human making or using of material artifacts in all forms and aspects" (Mitcham, 1978, p. 232). Furthermore, it is relevant to note that it is highly unlikely, if not impossible, that technologies will occur by chance, without being created by humans, "given the inherent knowledge and requisite organization of technology as a system that allows it to produce objects and perform techniques to achieve goals" (Carroll, 2017, p. 126).

To proceed, to define advanced manufacturing technologies, I will rely on the European Commission's definition. Advanced manufacturing technologies exist through advances and convergences of technologies, including digitalization. Advanced manufacturing technologies enable the creation of new production processes and/or the manufacture of new types of products and/or the emergence of new business models. The outcomes of advanced manufacturing technologies include products and services with higher added value, processes and products with increased environmental sustainability throughout the product life cycle, industrial competitiveness and resilience, employment creation, and improvement of job quality (European Commission, 2013).

Advanced manufacturing technologies are thus human-created means to create something beneficial, and that inherently requires knowledge and organization, in other words, management. Especially regarding advanced manufacturing technologies, it is not only about the creation of these new manufacturing technologies, but rather their diffusion throughout the economy and industry that contributes to innovation and growth at the level of society. Therefore, diffusion at the level of an industry or adoption at the level of an organization and interorganizational networks are highly relevant for economic growth (Arvanitis & Hollenstein, 2001).

Successful production transformation (i.e., the adoption of new manufacturing technologies) in manufacturing companies is increasingly important for the economy and society (Holmström et al., 2021). Technological developments have been influential in driving production transformation (Rehnberg & Ponte, 2018), and the digitalization of industrial value chains accompanied with new digital manufacturing technologies such as additive manufacturing (AM) are current examples of such technologies (Baldwin 2016). On a company level, advanced manufacturing technologies contribute to competitive capabilities and thus potentially to the performance of manufacturing companies (Skinner, 1996; Small & Yasin, 1997; Sun & Hong, 2002; Tracey et al., 1999).

New advanced manufacturing technologies are essentially innovations. Innovation is usually defined as the introduction of a new product or new quality of a product, the introduction of new processes to production, the introduction of a product to a new market, the acquisition of a new source of raw/semi-processed material, or the implementation of a new organization in any industry (Schumpeter, 1934). In this dissertation the focus is on advanced manufacturing technology innovations since the analysis is conducted from the perspective of AM as a specific technology. Production innovation would be another closely relevant concept if the focus were more generally on the production process perspective (Romero et al., 2017; Larsson et al., 2018; Larsson 2020).

A later definition of innovation is that it must aim to create new value in the form of new products, new services, or new organization network structures (Arlbjørn et al. 2011). Value is also expected by the focal organization developing or exploiting innovations, as it is also expected by customers who purchase the outcomes of innovations.

Since innovations are associated with new value, the term deserves further clarification, as value and value generation are both broad concepts (Lepak et al., 2007). The term "value" can be seen from a direct monetary perspective as the amount that customers are willing to pay for the goods that an organization provides (Porter, 1985). However, this view is argued to be too simplistic, and a broader definition acknowledges value as the difference between (broadly including sustainability aspects) benefits derived and costs incurred (Slater, 1997), enhanced competence, effectiveness, differentiation, or social rewards (Amit & Zott, 2001; Wilson & Jantrania, 1994). Value generation refers to activities that generate value (Slater, 1997), and innovations are a great means of creating value (Schumpeter, 1934). The term "value" is also used to describe and explain human motivations (i.e., human values) at a personal and cultural level (Schein, 1990), and this is distinct from the concept used when describing value creation from an operational perspective.

Besides the subject of innovation (product, service, method, etc.) and the new value it generates, innovations can be further defined based on the characteristics of innovation from the organizational newness, market, and complexity perspectives. From the newness perspective, innovations can be divided into incremental innovations, which, for example, can be optimizations, and radical innovations, which are usually completely new innovations (Freeman & Soete, 1997). What is to be noted is that the classification depends on the experiencer (Johannessen et al., 2001), meaning that there is no objective generic way to classify innovations when the organizational level is under observation. From the market perspective, innovations can be divided into sustaining innovations, which generate new value to existing markets, or disruptive innovations, which may create a completely new market (segment) or new value network that eventually disrupts the existing market or value network (Bower & Christensen, 1995). From the complexity perspective, innovations can be observed and classified based on whether the innovation is feasible on its own or needs other innovations to become feasible. In a situation where other innovations are needed, the term "systemic innovation" is used, which "corresponds to the type of innovation that only generates value if accompanied by complementary innovations. It opposes autonomous innovation, which can be developed independently of other innovations" (Takey & Carvalho, 2016, p. 97).

2.1.2 Technology innovation adoption

For innovations to generate value, they need to be adopted into use (Preece, 1991), or, even more fundamentally, for an invention to become an innovation, it needs to be adopted by someone in the social system (Rogers, 1962, 2003). Adoption of new manufacturing technology refers to the phenomenon of how a technological innovation comes to be used in certain ways and for certain purposes (Preece, 1991).

When shifting the focus to the adoption of technology innovations (AM being the innovation under study in this dissertation), relevant knowledge is found in the literature on innovation development, adoption, and diffusion. Perhaps the best-known frameworks are the technology acceptance model (Davis, 1989), the diffusion of innovations theory (Rogers, 1962, 2003), the theory of reasoned action (Ajzen & Fishbein, 1975), and the theory of planned behavior (Ajzen, 1985; Taylor & Todd, 1995).

According to these frameworks, various factors influence the adoption decision at the organizational level. Some examples include perceptions of an organization regarding the potential benefits and incentives of the technological innovation (Mansfield, 1993), such as general cost reductions, savings of inputs, higher improvement in product quality, flexibility and so on (Clark 1987; Milgrom & Roberts, 1990); innovation characteristics, such as compatibility, complexity, observability, trialability, and perceived uncertainty (Rogers, 1962, 2003); perceived usefulness and perceived ease of use (Davis, 1989); and anticipated barriers related to the potential use of new technology or to its adoption (Cainarca et al., 1990). Also, organizational characteristics are argued to influence innovation adoption and whether the organizational culture fits the innovation characteristics (Gallivan, 1998).

In addition to adopting technology within one company, the relevance of interorganizational networks is recognized (Arvanitis & Hollenstein, 2001; Linton, 2002). Organizations need to communicate with their networks of potential partners or collaborators about the technological innovation because innovation adoption is mainly an information processing activity within organizations (Talukder, 2014). Organizations can facilitate the diffusion of information about a technological innovation through their formal or informal networks, which has the potential to influence the probability of adoption (Frambach & Schillewaert, 2002).

However, all these frameworks portray innovation as a static and ready-to-use product with tangible functional features that can be confirmed ahead of time; thus, adoption is only dependent on making decisions based on the information gathered (Gallivan, 2001; Hirschman, 1987). According to these adoption frameworks, the fundamental challenge for potential adopters is obtaining the necessary facts to determine whether the innovation would meet their needs by providing "something" at a lower cost or with better effectiveness than the "something" they are now using (Hirschman, 1987; Hirschman 1980; Gatignon & Robertson, 1985). This dissertation does not, however, focus on studying the determinants of adoption decision making but on the process of adoption more broadly.

In addition to adoption frameworks that focus on factors and determinants of adoption success to either predict or explain adoption success, there is another literature stream that focuses on innovation adoption as a process. Process models describe the sequences of events that take place throughout adoption and implementation, with most stages focusing on what happens after the adoption decision is made (Gallivan, 2001; Prescott & Conger, 1995). Stage models are useful for describing and explaining how an adoption process unfolded, in what kind of sequence, through what kinds of events and contexts, and through certain interlinkages and temporal relationships between context, actions, and results (Gallivan, 2001).

The most relevant process models for this dissertation were developed by Rogers (1962, 2003), Preece (1991), and Tornatzky and Fleischer (1990), Zaltman et al. (1973). Zaltman et al. (1973) divided the adoption process into two steps: primary adoption of decision making at the high organizational level and secondary adoption, meaning implementation withing an organization. Rogers (1962, 2003) presented a five-stage adoption model: knowledge gathering, persuasion, decision, implementation, and confirmation. Preece's (1991) model followed the same principles but expanded the process into seven stages. Tornatzky and Fleischer's (1990) model also followed the same overall structure.

The focus of this dissertation is studying the AM adoption process to "capture the complex, over-time nature of the innovation process in organizations" as advocated by Rogers (2003, p. 361). The focus includes adoption decision making and initial implementation, as defined by Rogers (1962, 2003), Tornatzky and Fleischer (1990), and Zaltman et al. (1973). The earlier phases of the innovation process preceding adoption (awareness and/or knowledge gathering, persuasion, matching/selection) and the follow-up (routinization of adopted technology) (Rogers, 1962, 2003; Tornatzky & Fleischer, 1990), are not under focus in this dissertation.

Process models, however, like adoption decision frameworks, are based on assumptions about static and adopt-as-such innovations (Gallivan, 2001). Furthermore, the current understanding of technology innovation adoption frameworks is predominantly product-focused and does not sufficiently address advanced manufacturing technologies or the relation of alternative technology development paths stemming from manufacturing innovations (Yamamoto & Bellgran, 2013). For example, Rogers (1962, 2003) acknowledged the nature of the stages of technology development and its relation to adoption, but started from product innovation, which takes place through trial and error in a quest to solve a potential need (often radical innovation in high technology), moving to imitation (gradual improvement of product), technological competition, and lastly, standardization, where the production methods are optimized. Thus, manufacturing innovations take place last, but what if the manufacturing innovations emerge first?

Additive manufacturing represents no such static innovation that is ready to be used as is. First, there are many different AM technologies that are constantly technologically evolving, posing different technical possibilities, employing the principles of "growing" or building up an object. Second, AM machines as "the innovation to adopt" do not make sense alone, as they arguably do not directly fit into the current manufacturing methods. Additive manufacturing does not weld faster like a welding robot, nor does it cut more accurately like a laser cutter, nor does it ease the work of an expert welder like a lighter-weight angle grinder—to make a few comparative examples from metallic component manufacturing.

Earlier research has noted that the adoption of advanced manufacturing technologies (such as AM) may impose a systemic change on organizations and networks (Tyre, 1991). This means changes to every aspect of how production functions, and the adoption process resembles a research project (Tyre, 1991). Furthermore, if the technology innovation is systemic in nature, it implies the need for complementary innovations to become feasible (Takey & Carvalho, 2016), which potentially adds to the complexity of adoption.

The development of an innovation might be systemic (clustering innovations, in Rogers' terms, 1962, 2003), and, for example, the development of AM technologies has required innovations in many fields of science. Chesbrough and Teece (2002) argued that in this case, the development of systemic innovation usually takes place within an organization. This dissertation does not focus on the systemic nature of AM development but focuses on the adoption of AM.

The adoption of systemic manufacturing innovation is, however, a different phenomenon from the development of the systemic "underlying" innovation (AM). Especially relevant for the adoption of systemic innovations is the idea of technologies and their relation to further creating new technologies and innovations at a generic level (Liu et al., 2017), and the relevance of different types of organizations from producer and user side (Larsson, 2020; Larsson & Karlsson, 2019) There is a reason to expect that systemic change and the relation between technology and new innovations and systemic innovations means that advanced manufacturing technology adoption both requires and enables process and product innovations. Process innovation, in this context, can be defined as innovation that alters how processes (manufacturing and supply chain related in this dissertation) are conducted, and they can be either incremental or radical in nature. Product innovation refers to both incremental and radical innovations. Adopting systemic manufacturing innovation arguably benefits—if not even requires—collaborations between different organizations (Chesbrough & Teece, 2002), and it involves multiple mutually influencing, interconnected innovations as part of the value chain change (Maula et al., 2006; Mulgan & Leadbeater, 2013).

The justification for studying the adoption of advanced manufacturing technology innovations (with AM as the technology context in this dissertation) comes from multiple directions. For large-scale adoption of advanced manufacturing technologies, adoption is a relevant study because at the society or macro level this diffusion contributes to economic growth (which currently contributes to social welfare). It is relevant at the ecological level because it contributes to the efficient use of scarce resources. It is relevant to the competitive dynamics of the manufacturing industry because it contributes to the competitive advantage of companies and company networks. Managing technology adoption, in its simplicity, involves removing uncertainties and envisioning potentials, combining knowledge, and organizing the efforts in their networks. Furthermore, the current understanding of technology adoption is lacking in the context of adopting manufacturing innovations (Yamamoto & Bellgran, 2013) in contexts where successful adoption outcomes cannot be achieved by single users independently adopting technologies (Gallivan, 2001), and where the adoption of underlying technology requires complementary innovations in other systems. This dissertation aims to provide new knowledge on the special nature of systemic manufacturing innovation adoption in the specific context of AM adoption.

2.1.3 Interorganizational collaboration

The third major key concept addressed in this dissertation is interorganizational collaboration, which is relevant for both the adoption of new technologies (Arvanitis & Hollenstein, 2001; Chesbrough & Teece, 2002; Linton, 2002) and innovation (Chesbrough & Teece, 2002; Garud et al., 2013; Powell et al., 1996).

In its simplest form, interorganizational collaboration takes place between two organizations (creating a dyadic link), whereas the simplest form of interorganizational network requires collaboration between three (a triadic link) or more organizations (Nohria & Eccles, 1992).

Particularly in fast-developing or emergent technologies, interorganizational collaboration allows firms to collaborate and build on the strengths of other firms and, thus, legitimize a new technology, establish new industry standards, and create a bandwagon effect (Chesbrough, 2003; Garud et al., 2013; Van de Ven, 2004). These types of collaborations are intentional and aim for innovation, knowledge sharing, and capacity building, and the shape of such networks can be dynamic (Nohria & Eccles, 1992; Powell et al., 1996). Therefore, besides innovation taking place within one company, innovation can happen between two or more companies. When innovation is created within one company, the term "intra-organizational innovation" is used, and when innovation takes place between two or more organizations, the term "interorganizational innovation" is used (Santosh & Smith, 2008).

Systemic innovation (like AM) is often mistakenly seen as an outcome, and that outcome is adopted as such, when in reality it is a far more complex process spanning organizational boundaries (Chesbrough & Teece, 2002; Garud et al., 2013), and there is a reason to anticipate that adopting a manufacturing innovation is associated (positively) with the creation of follow-up and complementary innovations (Liu et al., 2017).

Previous studies of systemic innovation adoption have been conducted, but not in the context of advanced manufacturing innovations, and they have highlighted the relevance of interorganizational collaboration. For example, systemic innovation adoption in the energy industry has been found to be associated with interorganizational collaboration, especially in emerging industries (Andersen & Drejer, 2008). Organizations have an incentive to engage in knowledge transfer and solving problems in collaboration during the emergent stages of systemic innovation adoption because they share the interest to create an industrial foothold and challenge established practices, such as those associated with a competing but matured technology (Andersen & Drejer, 2008). Presumably, this collaboration is a way for organizations to generate more value than if they tried to solve these kinds of problems intraorganizationally (Powell et al., 1996). However, there is still a lack of knowledge about the connections between systemic innovation adoption, interorganizational collaboration, and value generation (Lavikka et al., 2021).

Interorganizational collaboration can be further understood through different conceptual lenses that focus on the relevant aspects of this phenomenon when multiple organizations have a mutual interest in something but from different perspectives. Interorganizational collaboration; dyads, triads, and networks; stakeholders (both primary and secondary); supply chains; and value chains all regard this same phenomenon of related actions of multiple organizations but from different angles. Interorganizational collaboration focuses on cooperation between multiple organizations (Nohria & Eccles, 1992). The network perspective focuses attention on the network level instead of on one-to-one collaboration (Nohria & Eccles, 1992). The stakeholder perspective attends to the interests and tasks (among other attributes) that organizations have in the networks during interorganizational collaboration (Freeman et al., 2010). The supply chain perspective focuses on the physical production and logistics that take place in interorganizational networks (Heikkilä, 2002). The value chain concept relates to activities that create value, starting from need and innovation and eventually leading to the establishment of new supply chains (Porter, 1985; Slater 1997).

Next, the stakeholder view, a lens for analyzing interorganizational collaboration, is further explained. Stakeholders are assumed to be part of organizational activities and are defined as "groups or individuals that have a stake in the success or failure of a business" (Freeman et al., 2010, p. xv). Often, stakeholders are defined from a focal organization's perspective to highlight which stakeholders the managers should pay attention to. Stakeholders in this case can be customers, suppliers, and employees (Freeman et al., 2010; Mitchell et al., 1997). For a finer definition, stakeholders can be divided into primary and secondary (internal/external). Primary stakeholders are shareholders, company employees, customers, suppliers, and sometimes even competitors—basically anyone that has a "stake" in the outcomes of an organization (usually a company). Secondary stakeholders, such as national governmental organizations, are external to the direct business or activities of an organization but may indirectly influence, for example, the innovation process (Freeman et al., 2010). These kinds of relations (interorganizational collaboration) with stakeholders have been increasingly considered an important way of developing innovations (Haeckel, 2004; Powell et al., 1996; Yaziji, 2004).

The next concept regarding a multiple organization view is the operationalization of these networks and interorganizational collaboration, namely supply chains and value chains. Supply chains are defined as a network of companies that transfer and process materials and information (highlighting manufacturing) between them to create profits (Heikkilä, 2002). The value chain usually starts with raw material and ends up delivering the final product to the customer.

The concept of the value chain considers more value-adding or value-generating activities, which can be partially outside of the manufacturing chain and begin with (customer) need and innovations as a means of value creation, contrasting the concept of value chain with that of supply chain (Porter, 1985; Slater 1997). Although the concept of value chain was originally invented for the internal issues of an organization (Porter, 1985), in this dissertation, the perspective is widened to cover the whole network of organizations relevant (Hansen & Birkinshaw, 2007; Slater, 1997) in advanced manufacturing technology innovation adoption.

Supply and value chains represent different forms of interorganizational collaboration, ranging from contractually based to mutually beneficial and symbiotic (Takey & Carvalho, 2016) collaboration. Both supply and value chains can also take the form of a network if the "chain" is not linear but is more complex. Therefore, the concepts of supply chain and value chain can both be viewed from the perspectives of different types of interorganizational collaboration, networks, and stakeholders.

These concepts help in seeing that under the same phenomenon, things happen at different levels and that these issues can be approached from different perspectives, which is argued to be important when analyzing innovations and their adoption (Eveland & Tornatzky, 1990; Linton, 2002).

2.1.4 Sustainability of manufacturing technology innovations

The fourth major key concept utilized in this dissertation is the sustainability (and responsibility as sub-theme) of manufacturing technology innovations, which is my attempt to provide a value-oriented view acknowledging ideologies and culture (Schein, 1990) for the dissertation. Schumpeter (1942) already recognized that innovations are prone to follow the big ideological shifts in society. The call for sustainable (and responsible) innovations has been identified as a major ideological theme that businesses and other organizations need to address (Nidomulu et al., 2009), and is highly topical at the present moment as illustrated, for example, by the latest Intergovernmental Panel on Climate Change (IPCC) report (2022).

Sustainability or sustainable development has long been framed into a simultaneous pursuit of three dimensions of economic development, social development and environmental protection operationalized as triple bottom line (Elkington, 1994). Currently, adopting a sustainable and responsible aspect to an organization's actions is likely to generate a positive welcome from stakeholders, as awareness is growing among them (Polonsky & Jevons, 2009). However, this concept of threefold sustainability has been criticized to give too much weight on economic sustainability, which allows business organizations to frame their competitiveness improvements as economic sustainability and downplay the other two aspects (de Figueiredo & Marquesan, 2022; Dyck & Silvestre, 2018; Livesey 2002; Holland, 1997; Gladwin et al., 1995). Manufacturing organizations, therefore, have a pressing need to combine and highlight ecological and social sustainability perspectives with profitable business (Säfsten et al., 2022)

From the institutional level, the United Nations' Brundtland Commission report defined the concept of sustainable development as follows: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43). Furthermore, responsible innovation is defined as "taking care of the future through collective stewardship of science and innovation in the present" (Stilgoe et al., 2013, p. 1570). Since the very definition of innovation is based on its ability to support organizational competitiveness and thus economic growth, sustainable innovations (and responsible innovations) focus on the consideration of social and environmental aspects, which can be easily neglected due to a short-sighted focus on economic growth (Owen & Pansera, 2019). This way sustainable innovation concept aims to support preferred ecological and social sustainability outcomes and to prevent unintended consequences of innovations (von Schomberg, 2013). For these reasons, the sustainability in innovations in this dissertation is considered majorly from environmental perspective. Social perspective of sustainability is touched upon as a part of stakeholder analysis.

Sustainable innovations (or sometimes sustainability-oriented innovations) are often divided into three categories: sustainability-relevant innovations, sustainability-informed innovations, and sustainability-driven innovations (Calabrese et al., 2018; Hansen & Grosse-Dunker, 2013; Jay & Gerand, 2015; Klewitz & Hansen, 2014). In sustainability-relevant innovations, the sustainability comes in the form of by-product–a process is incrementally innovated, and thus it consumes less energy. In sustainability-informed innovations, sustainability is not the main goal of the innovation but is purposely considered when designing products and processes–by using life cycle calculation tools or other sustainability indicators. In sustainability-driven innovations, sustainability is the starting point for innovation–in other words, innovation aims to solve a problem that is important for the environment or society (in terms of social sustainability and/or responsibility).

In responsible innovation, the notion of collective stewardship (Stilgoe et al., 2013) increases the need for research on innovation networks and the stakeholders who influence the sustainability and responsibility aspects of innovations. Stakeholders may thus have an influence on innovation, more generally to support the overall success of an innovation or even to pressure enhancements to the sustainability and responsibility of innovations (Pagell & Shevchenko, 2014; Ottosson, 2009; Van de Ven, 1986).

Both sustainability and responsibility in innovation can be studied through the lens of value. The aim of innovations is to produce knowledge and value (from a wide perspective, including monetary as well as other issues, such as air quality) (Owen et al., 2013). Thus, innovations that create more value in less harmful ways compared to the alternatives available can be seen as sustainable and responsible innovations from the outcome perspective (Dyck & Silvestre, 2018; Niaki & Nonino, 2018). In this dissertation, this outcome view is highlighted, and here, the innovation process is viewed from an outcome-expectancy perspective.

The rationale for including the sustainability perspective in technology adoption lies within the concept of value. As defined above, innovations aim to create value. Innovations are therefore adopted in order to realize and benefit from the value added by the innovation. As presented here, value can also be defined from the perspective of sustainability and responsibility (Freudenreich et al., 2020; Dyck & Silvestre, 2018), and value creation in collaboration (Rahnama, 2022) throughout the whole value chain (Säfsten et al., 2022). For sustainable innovation the "Primary motivation is socio-ecological "value creation" while contributing to financial viability" (Dyck & Silvestre, 2018, p. 1596).

2.2 Managing the adoption of additive manufacturing

This chapter presents AM, the technology context of this dissertation. First, AM as an advanced manufacturing technology innovation is explained. Then, in sections 2.2.2 and 2.2.3, previous AM-specific adoption studies are reviewed, followed by a review of previous AM supply and value chain studies. These present the existing knowledge regarding the first research question, "How do organizations manage the adoption of additive manufacturing in their interorganizational networks?". Section 2.2.4. presents a review of previous AM sustainability-related studies and illustrates the current knowledge regarding the second research question, "How can organizations address sustainability through AM innovations?".

2.2.1 Additive manufacturing–an advanced manufacturing technology innovation

Additive manufacturing is an umbrella term that refers to many types of technological approaches that allow organizations to obtain a desired geometry digitally from 3D model designs and thus to build objects by increasing materials, such as metals, ceramics, plastics, or composites, usually layer by layer (ASTM, 2012; Holmström & Partanen, 2014), by contracting it from subtractive or forming manufacturing technologies (Spina & Compañó, 2021). Additive manufacturing is considered an advanced manufacturing technology innovation.

Besides being merely a technological innovation, AM has the potential to alter industrial manufacturing value chains more drastically than simply replacing one machine with another in the production process (Stentoft et al., 2016). This kind of innovation can therefore be considered radical and separate from incremental innovations to enhance the Schumpeterian throughput of a company, but is increasingly tied to what is being manufactured with the technology. Additive manufacturing as an ongoing radical digital manufacturing technology innovation is even anticipated to have disruptive effects within industrial organizations and possibly within complete industries throughout the value chains (Berman, 2012; Ortt, 2017; Ortt, 2016; Sasson & Johnson, 2016; Steenhuis & Pretorius, 2016).

The various advantages of employing AM technology have been explored in previous research. These advantages include product customization, the capacity to produce small batches efficiently and quickly, the flexibility and adaptability of designs, supply chain simplicity, and resource consumption and waste reduction (Berman, 2012; Flores Ituarte et al., 2016; Holmström et al., 2010; Khajavi et al., 2014; Niaki & Nonino, 2017; Weller et al., 2015). Several studies have also developed theoretical frameworks for AM application recognition and AM added value (Chaudhuri et al., 2021; Fontana et al., 2019; Knofius et al., 2016; Lindemann et al., 2015; Rylands et al., 2016; Stentoft et al., 2021).

The majority of organizational-level AM studies are theoretical and visionary in terms of research, with actual case studies still being rare–probably due to the technology's newness—and, although the technological underpinnings and techniques of AM production have been widely explored, the business implications are still mostly under studied (Ortt, 2016). Therefore, more empirical research is needed. With the emergence of AM as a new, advanced manufacturing technology, it is no longer apparent how components for products, assemblies, and tools are produced, supplied, marketed, or purchased, or what positions and tasks different companies are taking in their specific supply networks–or even what should be manufactured with this novel and emergent technology in the first place.

2.2.2 Adoption of additive manufacturing

The rate of AM technology diffusion at the industry level is determined by how different firms employ the technologies and build commercialized solutions based on them. Previous research has looked at the overall process of AM adoption in businesses (Mellor et al., 2014; Oettmeier & Hofmann, 2017; Rylands et al., 2016; Sandström, 2016), where the research on technology adoption and diffusion (Davis, 1989; Rogers, 1962, 2003) formed a baseline. Earlier research has already noted that focusing only on technical and economic issues is insufficient when adopting AM (Farooq & O'Brien, 2012). It is likely that strategic production plan changes will be needed when determining whether or not to use AM in their industrial parts production, so manufacturers should think about the potential implications for their supply networks, processes, and management (Oettmeier & Hofmann, 2016).

For AM to be diffused industry-wide, it must be adopted at many levels (Steenhuis et al., 2020), which underscores the importance of viewing AM as a systemic innovation. Companies that manufacture AM machines commercially adopt the concept of AM–building up objects, which leads to innovations in AM machines, materials, and software. They then sell these machines to businesses that use them to create prototypes or commercial goods and adopt AM processes. Finally, customers must then adopt AM-produced products (Steenhuis et al., 2020).

Companies in different positions must manage complex innovation and socio-technical processes to integrate the utilization of AM technologies into profitable business. As a first step, low-volume production using AM as a new manufacturing opportunity should be piloted (Flores Ituarte et al., 2016). Furthermore, companies have identified at least two different possibilities when starting the use of AM: they can purchase ready-made AM parts (contract manufacturing or services) or invest in AM machines themselves (Oettmeier & Hofmann, 2016), and regardless of the choice, technology-related, company-related, market structure-related, and supply chain-related issues have to be taken into consideration (Oettmeier & Hofmann, 2017).

The large number of studies on AM adoption cover both large and small businesses, and they emphasize the capabilities and requirements of AM technology (Deradjat & Minshall, 2017; Flores Ituarte et al., 2016; Niaki & Nonino, 2017; Oettmeier & Hofmann, 2016, 2017; Stentoft et al., 2021). Moreover, a number of studies have identified some of the determinants, drivers, and challenges to industrial and organizational AM adoption (Chaudhuri et al., 2018; Cohen, 2014; Delic & Eyers, 2020; Fontana et al., 2019; Marak et al., 2019; Oettmeier & Hofmann, 2017; Schniederjans, 2017; Schniederjans & Yalcin 2018; Sobota et al., 2021; Tsai & Yeh, 2019; Yeh & Chen, 2018). These studies show evidence that AM technology is not a solution for all manufacturing problems nor is it suitable for everything manufacturing-related, and it has its own trade-offs compared to traditional manufacturing. Table 2 presents the previous empirical studies on AM adoption.

Table 2. Summary of previous empirical studies on AM adoption

Study	Method and context	Main findings
Mellor et al. (2014)	Method: Single case study Context: Both polymer and metallic AM in-house manufacturer	Framework of relevant factors in AM implementation created and tested.
Flores Ituarte et al. (2016)	Method: Single case study Context: Polymer AM applications, end-use components	AM technologies are not yet diffused to the contemporary supply chain structures; strong barriers are existing in the areas of utilize AM in engineering applications
Oettmeier & Hofmann (2016)	Method: Two-case study Context: AM application: prototypes and end-use components	AM influences interorganizational processes, management processes, and supply chain processes.
Rylands et al. (2016)	Method: Two-case study Context: Metallic AM application, production process (tooling)	Implementation of AM implies a shift in value proposition of a product and supply chain; AM complements traditional manufacturing.
Sandström (2016)	Method: Exploratory desk research Context: Polymer AM in the hearing aid industry	Adoption of AM brings benefits, such as lower costs and higher quality. Operational and technological challenges are present in the adoption process.
Deradjat & Minshall (2017)	Method: Multiple-case study of 6 firms Context: Polymer AM, dental, and medical implant manufacturers	Implementation of AM implies different considerations depending on the stage of implementation, maturity of AM technologies, and company size.
Niaki & Nonino (2017)	Method: Exploratory study with 16 firms Context: Metallic AM, end-use implants	Implementation of AM has increased the productivity of metal AM products.
Oettmeier & Hofmann (2017)	Method: Questionnaire survey Context: AM generally, with a wide range of materials and applications.	Supply chain-related factors have a strong influence on AM adoption.
Niaki et al. (2019b)	Method: Survey with 105 companies, AM generally Context:	Adoption of AM is beneficial in specific context, where the organization's experience, scope where AM in implemented and what material is chosen.
Stentoft et al. (2021)	Method: Case study Context: Metallic AM, as well as polymer, highlights collaboration through associations	Barriers to AM adoption identified, argued that those can be overcome through participation in an AM business association

Investing in technological capacity building (Weller et al., 2015) or in design and innovations (Mellor et al., 2014), developing strategic value chain changes (Flores Ituarte et al., 2016), and developing specialized know-how are identified examples of ways to overcome the challenges of AM adoption (Oettmeier & Hofmann, 2016). Moreover, the possibility that AM can add value to both the product and the whole value chain has been identified as relevant to AM adoption (Ballardini et al., 2018; Fontana et al., 2019; Kritzinger et al., 2018; Rylands et al., 2016). These studies, however, lack in-depth explanations or characterizations of successful interorganizational adoption of AM technology (in the field of metallic and ceramic AM).

Even though AM has already been around for over three decades, its adoption has been limited so far (Steenhuis & Pretorious, 2017). Because of this, the extent to which AM will change manufacturing industry and society as a whole is unknown, and more in-depth research is needed about the characteristics of AM adoption (socio-technical studies in very specific situations) (Maresch & Gartner, 2020; Mellor et al., 2014; Steenhuis & Pretorius, 2017), and to understand the organizational constraints and requirements of technology adoption in various industrial settings (Flores Ituarte et al., 2016), especially in an interorganizational context (Oettmeier & Hofmann, 2017).

2.2.3 Supply and value chains in additive manufacturing

The two related concepts of supply chains and value chains, where interorganizational collaboration takes place, are relevant in studying AM adoption, as there are signs that a single company cannot reap the full benefits of AM on its own, and that AM adoption necessitates the participation of several supply chain players (Oettmeier & Hofmann, 2017).

Two types of supply chain are especially relevant for AM adoption and operation. The first type of supply chain concerns AM machines and considers AM machine manufacturers and suppliers, which both sell AM machines to other companies that use AM machines in their own business (Mellor et al., 2014). The innovation value chain here relates to the innovation of new AM machine and process types and considers the adoption of the AM concept (Steenhuis et al., 2020). The second type of supply chain is relevant for goods manufactured using AM equipment and concerns supply chains from material suppliers to AM (contract) manufacturers and their design and software partners, all the way to their customers and other suppliers (Mellor et al., 2014). The innovation value chain here relates to the adoption of AM as part of industrial value chains and emphasizes both process and product innovation creation and adoption (Steenhuis et al., 2020). In the case of this dissertation, the focus is solely on the latter types of supply and value chains.

Previous conceptual studies have considered the possibilities of AM adoption in supply chains. It is expected that AM may potentially enable simpler supply chains, shorter lead times, and lower inventory rates, which are likely to reduce operations costs—or AM may enable altogether new manufacturing configurations (Campbell et al., 2011; Holmström et al., 2010; Petrick & Simpson, 2013; Sasson & Johnson, 2016; Steenhuis & Pretorius, 2017). Some of the empirical AM adoption studies have identified supply chain level implications (Oettmeier & Hofmann, 2016; Rogers et al., 2016; Rylands et al., 2016; Thomas, 2016) and have noted that companies should consider the potential implications in supply chain levels in the adoption process and management. This considers the primary stakeholders in the supply and value chains.

The involvement of secondary (external) stakeholders in innovation processes has only been covered briefly in prior AM research. According to empirical studies (Beltagui et al., 2020; Koch, 2017; Monzón et al., 2015; Rylands et al., 2016), external stakeholders deserve more attention in the AM field. External stakeholders can support the execution of knowledge transformation with regard to AM (Rylands et al., 2016), as trade organizations and engineering associations specify the need for standards for the standardization organizations to create new standards (Koch, 2017; Monzón et al., 2015). Finally, organized customer groups or associations representing their customers can provide customer-need knowledge and even exert pressure on AM manufacturers who are still in the design phase of a new product to consider sustainability issues (Beltagui et al., 2020). All of these aspects are relevant for the successful adoption of AM and to steering it in a sustainable and responsible direction. This explicates a research need to understand the participation and influence of external stakeholders during AM adoption. Table 3 presents previous AM supply-chain-related studies.

Table 3. Summary of previous studies on AM supply chains

Study	Method and context	Main findings
Holmström et al. (2010)	Method: Conceptual Context: Metallic AM	The potentially emerging supply chain benefits (improved service and reduced inventory) make AM very relevant for spare parts supply.
Campbell et al. (2011)	Method: Conceptual and experimental cases Context: AM generally	Supply chains are expected to shorten or simplify, designs instead of products are moved in the digitalized supply chains, products may be manufactured on demand.
Petrick & Simpson (2013)	Method: Conceptual Context: AM generally	AM enables better customer collaboration in the design phase of new products. AM supply chain is expected to be non-linear, localized collaboration with ill-defined roles and responsibilities
Monzón et al. (2015)	Method: Conceptual, desk research Context: AM generally	Standards are needed to enable AM diffusion into supply chains, standardization organizations help with this among other stakeholders
Oettmeier & Hofmann (2016)	Method: Two case studies Context: Polymer AM from the hearing aid industry, SME firms operating their own AM machines	Different processes like order fulfillment, manufacturing, and supply chain management are influenced by the adoption of AM
Rogers et al. (2016)	Method: Conceptual, with evaluation of public data Context: AM generally with a service provider focus	Different kinds of AM service models are emerging, new supply chain structures are established together with new AM applications
Rylands et al. (2016)	Method: Two case studies Context: Metallic AM	Value stream changes in products and supply chains after the adoption of AM; customers are able to engage in the design process better than before
Thomas (2016)	Method: Comparative single-assembly supply chain cost analysis Context: metallic AM	AM influences both the manufacturing and the supply chain process level
Sasson & Johnson (2016)	Method: Conceptual Context: Metallic AM	Suggests alternative supply chain scenarios for utilizing AM
Oettmeier & Hofmann (2017)	Method: Conceptual Context: AM generally	Supply chain-related issues may influence the decisions to adopt AM technology because AM may offer novel possibilities for both upstream and downstream of a company's supply chain
Steenhuis & Pretorius (2017)	Method: Exploratory study through desk research Context: AM generally	Adopting AM may require reforming supply chains
Koch (2017)	Method: Case study Context: AM generally	Stakeholder groups help establish standards that enable interorganizational collaboration
Beltagui et al. (2020)	Method: Case study combined with system dynamics modelling Context: AM supply chain (polymers highlighted)	AM applications enabled to overcome the supply chain flow issues caused by the occurrence of limited availability of goods that are typically mass manufactured.

Since it is expected that diverse organizations collaborate to produce value through AM, there is a need for research in the domains of partial or complete AM supply chains covering multiple stakeholders. More research is also needed regarding the changes that occur in AM supply chains, the types of innovations required for AM supply chains and value chains, and the complementarity of these different types of innovations for AM adoption.

2.2.4 Sustainable additive manufacturing innovations

Additive manufacturing can become one of the solutions for more sustainable manufacturing (Beltagui et al., 2020; Ford & Despeisse, 2016). This is also emphasized in the European context, where there are high sustainability- and responsibility-related expectations for AM to support economic growth (CECIMO, 2017; 2019).

Regarding sustainability outcomes, AM has two major research streams: the sustainability of AM processes and the sustainability of AM-manufactured goods. The first research stream's main purpose regarding sustainability is to study and develop (digital) advanced manufacturing technologies to save resources by being additive instead of subtractive (Berman, 2012; Chen et al., 2015; Gao et al., 2015; Holmström & Partanen, 2014, Niaki & Nonino, 2018). At the supply chain level, AM is expected to reduce energy consumption in logistics and transportation (Chen et al., 2015; Gebler et al., 2014). This could be achieved by providing on-demand production of components and spare parts, which gradually moves the focus from the manufacturing process into the next phase of the goods lifecycle. In addition to simpler logistics, AM spare parts contribute by extending the lifecycles of products and providing alternative supply chain participants with the chance to take on new responsibilities and develop sustainable solutions to industry-level challenges (Holmström & Partanen, 2014; Mellor et al., 2014; Gao et al., 2015). New sustainable solutions are possible to achieve with product and process redesign, innovating for materials by developing operational models for make-to-order components, and developing closed-loop supply chains (Ford & Despeisse, 2016). The sustainability of AM is estimated to be a complex issue because it has overall implications for supply and value chains (Ott et al., 2019). This kind of sustainability seems to be often framed into economic sustainability as these innovations are lowering the costs or improving performance (Niaki et al., 2019a; Niaki et al., 2019b Niaki & Nonino, 2018), without highlighting the broader scope of value that can be added trough AM.

As the cost savings of energy or logistics savings are not only offering economic benefits, but produce also other types of value in a broader scope, and this should be studied and discussed more often.

However, in a recent AM adoption study, Niaki et al. (2019a) noticed that sustainability is not a feature that drives AM implementation, contrasting the studies expecting that sustainability would be an important aspect of AM adoption (Ford & Despeisse, 2016; Gebler, 2014). In another recent study, Maresch and Gartner (2020) noticed and identified stakeholder groups as important for the future success of AM and AM innovation. They proposed that education and training would increase the adoption and application of AM, and organizations can act as knowledge hubs, providing access to trying different technologies and finding suitable partners through which sustainability aspects will become increasingly important in the success of AM (Maresch & Gartner, 2020).

Therefore, there is a research need to create understanding of the sustainability of AM and its relation to AM adoption and diffusion. The lack of understanding of the benefits of sustainable AM limits AM adoption in practice, and potential opportunities remain unclear (Holmström et al., 2017). The focus of this dissertation is on the intersection of sustainable AM innovations (from a goods perspective) and AM adoption. Table 4 presents the previous studies on AM sustainability and responsibility.

Table 4 reveals that the area of sustainability is an under-researched area, where many of the studies are conceptual or focus more on the technical process of AM and its sustainability. Some studies argue that the full lifecycle and process, as well as the outcome (products) of AM innovation need to be taken into consideration. This dissertation focuses on the issue of AM innovation outcomes and its sustainability potential as part of AM adoption.

Table 4. Summary of previous studies on AM sustainability

Study	Method and context	Main findings (process/outcome)
Petrovic et al. (2011)	Method: Experimental case study Context: AM generally (highlights metal)	AM processes save raw material (process). AM enables high added value and functionality of AM goods, potential for sustainability (outcome)
Berman (2012)	Method: Conceptual Context: AM generally	Compares process parameters to traditional manufacturing, potential for more sustainable processes (process)
Gebler et al. (2014)	Method: Conceptual (testing with quantitative database analysis) Context: AM generally (highlights polymers)	Sustainability of AM's lifecycle stages are production (feedstock, manufacturing, and logistics), using, and end-of-life; all of these needs to be evaluated (process and outcome)
Chen et al. (2015)	Method: Conceptual Context: AM generally	AM as a paradigm has potential to enhance sustainability and responsibility. Goods and spare parts may be produced only when need arises, this allows using minimal amount of raw materials and reduces transportation impact (process)
Gao et al. (2015)	Method: Experimental multi-case study Context: AM generally	AM saves raw material but currently is energy intensive (process) acknowledges full product life cycle (outcome)
Ford & Despeisse (2016)	Method: Exploratory case studies (publicly available) Context: AM generally; cases are obscure	AM sustainability opportunities may exist across the lifecycles of products and raw materials, This is enabled by redesigning the products and processes, improving novel raw material input processes, enabling on demand components, and in best cases allows circularity (process and outcome)
Holmström et al. (2017)	Method: Conceptual Context: Metallic AM spare parts (also other materials); operational design model development	Improving the sustainability of AM products and processes through AM, designing the products, logistics, usage, and post-selling service-operations in new ways is needed (process)
Niaki et al. (2019a)	Method: Multistage survey Context: AM generally (highlights polymers and prototyping)	Environmental and social benefits cannot only on their own motivate firms to adopt AM, environmental and economic performances are intertwined (process)
Ott et al. (2019)	Method: Conceptual Context: Metallic AM spare parts; cost model development	Sustainability over a product lifecycle shows potential of AM but requires calculating model development (outcome)
Beltagui et al. (2020)	Method: Case study combined with system dynamics modelling Context: AM supply chain (highlights polymers)	Adoption and diffusion of AM broadly may open possibilities for companies to utilize co-design (process)
Maresch & Gartner (2020)	Method: Multi-perspective technology foresight Context: AM generally (highlights polymers)	Sustainability is increasingly important for AM and may be introduced by innovative firms. Full life cycle costs are the most relevant for AM. Stakeholders support firms familiarizing themselves with AM (outcome)

3 METHODOLOGY

3.1 The philosophical positioning

When conducting research, it is important to acknowledge the assumptions behind the inquiry about ontology (what is real and what is reality), epistemology (what can be known and what is knowledge), and human nature (Morgan & Smircich, 1980). As technology and innovation are human-made and adopting them into use and using them, for example, for manufacturing (as in this dissertation), this forms a social phenomenon that positions this study under the label of the social science of technology and innovation.

This dissertation follows the philosophy of science tradition of interpretivism-constructivism, which was developed as a criticism of the positivistic paradigm that implies that there is single objective reality (Lincoln & Guba, 2000). The interpretivism-constructivism is based on an anti-realist ontology, which acknowledges that there are multiple realities that are subjectively constructed (Lincoln & Guba, 2000). The goal of this research is not to search for one objective truth, but to try to generate new knowledge and understand the complex world of lived experience from the perspective of those who live it (Schwandt, 1998). The epistemology of constructivism is based on relativism (Mir & Watson, 2000), meaning that knowledge is always relative to such things as society, culture, time, place, the conceptual view, and personal understanding (Siegel, 2004).

This viewpoint serves as a critical approach to reductionist theories of technological determinism and technological imperative. Technological determinism argues that technological development determines social structure and culture (Smith & Marx, 1994). The strongest form of technological determinism is the technological imperative, which argues that all possible technological advancements are going to be realized (Shallis, 1984). From the philosophical viewpoint of constructivism, technological development is never deterministic but is realized through the actions of humans, and even if technological advancements are possible, it does not necessary mean that those should be developed.

Following interpretivism-constructivism does not mean that the "reality" experienced is not real in terms of alleging that reality would be collective imagination. People's ability to socially construct reality enables a common understanding that allows us as people and as researchers to rationalize reality. The shared and socially constructed reality prone for sedimentation (Scott, 2014), which creates sometimes longer and sometimes briefer stability with regard to social phenomena such as emergent technology adoption. This stability is the reality for justifying scientific inquiries.

The other justification—or rather the need to study socially constructed phenomena such as technology and technology adoption—is well argued by Eveland and Tornatzky (1990, p. 50): "Innovation as a thing and action; technology as inseparable from human values and purposes; and technological innovation as complex interaction of people, scientific concepts, aspirations, and consequences. The more we learn about the components of those processes, the more we realize that the whole remains beyond our grasp. But after all, human efficacy is always at the margin; whatever we can find out that helps us avoid being whipsawed by our own systems is better than nothing".

Finally, in addition to interpretivism-constructivism, the research for this dissertation was further guided by pragmatist philosophy by focusing on the human need for the research and acknowledging that the "truth" is not the aim of this study, but the usefulness of the findings for society (McDermid, 2006). This dissertation focuses more on understanding and creating new knowledge to fill the needs of society and openly supports technological development and its adoption, rather than testing theories, which is usually the aim of pragmatism. In other words, the core of this dissertation is to understand the adoption of emergent technology, how to manage and support it, and how to steer the development into a more responsible and sustainable direction.

3.2 Research design

This dissertation was conducted using an Article compilation of four publications, all of which used qualitative research approaches. Qualitative research constitutes an array of different methods but is basically a means of interpreting techniques to describe, decode, or otherwise come to terms with meaning instead of frequencies (van Maanen, 1979). Qualitative research emphasizes processes that occur naturally in social activities and the meanings of social actors to understand a phenomenon (Gephart, 2004).

Articles I, II, III, and IV form a sequential series of studies. In a sequential research approach, different methods and timing enable further interpretation and explanation of the phenomena under observation (Creswell, 2009). For emerging manufacturing technology, a sequential research design allowed the study of technology adoption and the emergence of value chains. Figure 2 illustrates the sequential research design.

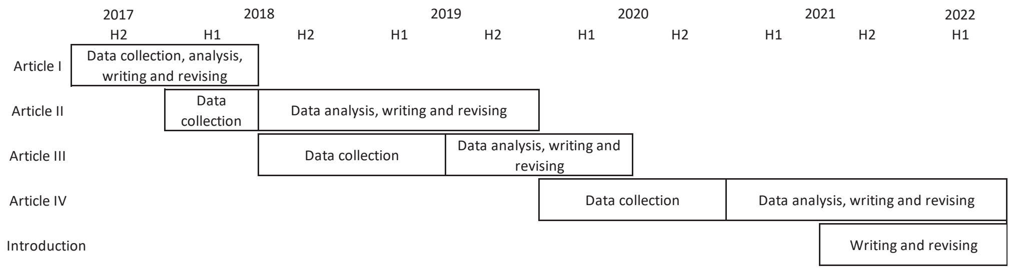

Figure 2. The sequential research design of this dissertation

The first three articles utilized an explorative research design. First, two articles were designed as explorative interview-based studies. The third article was designed as an exploratory expert panel study. An exploratory research design was chosen because of the emergent nature of the phenomenon and the limited previous research concerning AM and its innovations across the different supply chain positions. Exploratory research design is usually used for a problem that has not yet been thoroughly researched (Shields & Rangarjan, 2013). The goal of an exploratory research design is not necessarily to show conclusive evidence but to create a new understanding about a phenomenon (Saunders et al., 2012).

Exploratory research is a combination of inductive and abductive processes of reformulating and changing explanations and theories, since the process of sense-making of research object is a gradual process that resembles learning (Reiter, 2017). Exploratory research might not thus be pure discovery, since the researcher already has knowledge about the phenomenon, and new empirical evidence is used to modify, adapt, or specify theories so that what is being studied is making more sense to the researcher and is then better explained and better understood based on what is already known (Reiter, 2017).

Article IV employed a retrospective multiple-case study. Section 3.3 explains how the casing was done. A multiple-case study design enables the study of a phenomenon in its natural, real-life context, with many possible data sources (Piekkari et al., 2009). Real-life contexts and multiple data sources enable the researcher to formulate a holistic explanation of the cases under study (Ragin, 1992). Furthermore, multiple cases can be jointly studied to compare and complement each other and to offer information on the core phenomenon (Stake, 1995; 2005). A case study is also especially suitable for studying events, decisions, projects, and processes (Thomas & Myers, 2015).

A sequential design was needed because in the beginning of this thesis in 2017, the industrialization of AM was just emerging, and only a few pioneering companies had adopted the technology. As the research aim was to understand and support the development of the manufacturing industry, there was first a need to understand the challenges and barriers to adoption (Article I), the potential needs for innovations in the supply chain (Article II), and the emerging supply chains and stakeholders in AM innovation networks (Article III). As time passed, more and more companies started to actually adopt the technology, which opened up the opportunity to study the adoption from interorganizational and value chain perspectives through an in-depth case study (Article IV).

3.3 Research context

As it is composed of an article compilation, this dissertation employs a multi-level multi-source qualitative study. The contexts of each article are relevant to interpreting the findings and are explained in this section. Articles I, II, and IV are from the context of machine manufacturing and process industry manufacturing in Finland. In this context, the diffusion of metallic AM is just emerging, and this provides a good opportunity to study early adoption at the organizational and network levels.

In Article I, the participating informants were all from SMEs, as this group of companies was estimated to be relevant for AM adoption locally and Europe-wide. In Article II, the informants were from SMEs and large companies, and some of the SMEs were the same companies as in Article I. By adding large companies, the context of the study was expanded to cover multiple positions in machine building and process industry manufacturing supply chains. The potential AM applications in this sector range from tooling to functional parts all the way to spare parts for machines and processing plants.

The context for Article III is different, as the participants were all from the same EU Horizon2020 research project. The context covered both metal and ceramic AM in Europe. Organizations relevant to AM innovations were included among the informants and ranged from SMEs to research organizations. The industries relevant to the informants were the automotive and the biomedical industries. The relevant applications were tooling and spare parts of metallic AM in the automobile industry. In the biomedical industry, both metals and ceramics are relevant, and their applications have been delimited to biomedical implants.

Article IV is a multiple-case study. The casing was done by focusing on AM innovation projects, which included several organizations, and the AM value chain was adopted by the large product owner companies (two large companies). Other organizations included in the projects were an industrial design company, two different AM service and contract manufacturing providers, and two contract manufacturing companies. In each of the two cases of AM innovation projects (the second case having two sub-cases), the AM innovation project was formed based on the specific product and the network of companies involved in the AM adoption. The cases were intentionally sought and selected to represent AM innovation projects during which AM technology was adopted; they involved multiple firms in the value chain and featured a specific product. Another selection criterion was that AM technology was used in production after innovation and development (i.e., was adopted), so the focus was on the end-use components in production instead of only on the prototypes used during development. The first case represents a functional part that was developed using AM as a production method for processing plant machinery. The second case involved two spare parts that were used in the operation of logistics machines.

3.4 Data collection

The data for the first two explorative and qualitative studies were collected through in-depth qualitative semi-structured interviews with industry experts. Interview data were supported by data collected in workshops with industry experts. The data collection process for the third explorative article was iterative. First, a focus group workshop with experts was organized. Then, based on the results of the workshop, a qualitative open-ended survey was designed and sent to the same experts who were present in the first workshop. The results of the survey were further developed in a second workshop. Data for the fourth multiple-case study article were collected through in-depth semi-structured interviews accompanied by supporting company documents as secondary data. Table 5 summarizes the data collection method, data, and data analysis methods for each article.

Table 5. Data collection and data analysis of the articles

Article	Primary data	Secondary data	Data analysis
Article I	21 semi-structured interviews in 17 companies. Durations: 40–98 minutes. Two workshops with industry participants	An additional two workshops with industry participants	Inductive qualitative thematic analysis. Three coding rounds: initial, focused, and elaborative and focused coding (most important codes thematically categorized with use of framework from literature).
Article II	25 semi-structured interviews in 20 companies. Durations: 40–108 minutes. Three workshops with industry participants.	13 companies displayed their company's internal documents. Additional two workshops.	Inductive qualitative thematic analysis. First round initial coding, second round structural coding, followed by pattern coding and categorization into emerging themes from the data
Article III	11 qualitative open-ended survey responses, two workshops with 20 and 21 participants		Inductive qualitative thematic analysis. Stakeholder mapping and descriptive coding, followed by structural and process coding
Article IV	12 semi-structured interviews from 7 companies. Durations: 30–90 minutes.	Supplementary open-ended discussions after formal interviews with 11 key informants from the involved companies. Six interviewees displayed their company's internal documents.	Inductive qualitative thematic analysis. First round initial coding, second round pattern coding both thematically and chronologically, finalized with focused coding

Semi-structured interviewing was the main primary data collection method for the articles of this dissertation. In qualitative research, interviewing is among the most common (if not the most common) data collection methods (Bluhm et al., 2011). In interviewing, one-on-one interviews are usually arranged with relevant key informants who are identified by the researcher, usually with help from some contact persons from the organization that is under research interest (Creswell, 2009; Gorden, 1987). The interviews arranged for this dissertation's data collection followed these guidelines. The most suitable informants were sought based on a database of companies interested in and working with AM in Finland for Articles I, II, and IV, as explained in section 3.3. The informants were contacted and either directly agreed to the interview or, in some cases, suggested another relevant person from their organization. Voluntary participation was sought. The interviews for Articles I and II were partly one-on-one interviews, but some were conducted together with another researcher from the Välkky project. Interviews for Article IV were only one-on-one interviews.

The interviews were all semi-structured, meaning that interviews were conducted relying on pre-determined themes or key questions, but not in a way that would restrict the discussion with the informant (Barriball & While, 1994). Allowing informants to speak openly about a pre-determined theme and the opportunity for the researcher to ask probing questions raised by the comments of interviewee are benefits of semi-structured interviewing, which is especially suitable for capturing perceptions about complex issues (Barriball & While, 1994). During the interviews, pre-determined themes ensured that similar themes were covered in each interview, but the discussions varied naturally as each informant openly told their views, and I as an interviewer asked probing questions relative to the information that informants shared.

The interviews were all recorded. The interviews for Articles I and II took place face-to-face with informants (pre-COVID-19), whereas interviews for Article IV were conducted using video calls (during COVID-19). Interviews for Articles I and II were transcribed, and then the transcriptions were corrected before they analysis, as suggested by Creswell (2009). The interviews via video calls allowed the key informants to provide internal company documents with screen sharing to visualize the product innovations and the different phases that took place during the innovation process. These interviews were recorded, resulting in digital audio/video files. The analysis was conducted using Atlas.ti software, which allowed coding of the interviews directly from the recorded video call files. In this way, additional material could also be coded, as suggested by Tessier (2012). Furthermore, during each interview, handwritten notes of initial ideas for codes and preliminary ideas for analysis were documented to take advantage of the original situation and the situational intuition of the interviewer (Tessier, 2012).

The second primary data collection method in the articles of this thesis (Articles II and III) was workshops and expert focus group workshops. Workshops are increasingly used in qualitative research (Storvang et al., 2018). Collecting data in workshops allows the researcher to observe the participants and co-create the data together with informants. The data from workshops can be in the format of notes or memos and products of the workshop in the form of sketches or models (Storvang et al., 2018), as was the case with the data used in Articles II and III.

Workshops were combined with interviews in Article II, and they served both to generate an overview of the research subject and to guide the interview outline planning. Workshops were used as well for triangulation purpose for supporting the findings from interviews. In contrast, the workshops used for data collection for Article III were conducted more as a group interview with facilitated exercises to produce models and charts of the subject. These data were used in the main analysis in Article III, whereas in Article II, the workshop data had more supporting and validating aspects in the analysis.

The last primary data collection method utilized in Article III was a qualitative open-ended survey. Surveys with open-ended questions are frequently utilized in qualitative and explorative research (Allen, 2017). This method allows informants to take time and write their answers to open-ended questions (similar to themes in semi-structured interviews, or slightly more focused) without the necessity of engaging in discussion (Allen, 2017). This, of course, inhibits the possibility for probing questions. In the data collection for Article III, which also relied on workshop data, an open-ended survey was used as an efficient way to collect detailed information from the informants, based on the issues already discussed in a workshop.

As a more philosophical note about the data collection, it must be acknowledged that the data are not actually "collected" like one would collect stones or flora from nature and study them. The data is more accurately constructed or manufactured by the cognitions of the informants and the researcher, as well as by the interplay of the informants and the researcher (Yanow et al., 2014). The intention, however, is of course to handle the data "collection" as truthfully as possible, but possible biases in human science have to be acknowledged, and it is important to note that the data and findings from it are always relational (Silverman, 2013).

3.5 Data analysis

Data for the first three articles were analyzed abductively with the frameworks developed from previous studies in the field, as these are considered suitable for exploratory research (Reiter, 2017). Specifically, this means that codes emerged from the data, but they were either categorized with existing themes or the existing themes allowed the identification of relevant issues into codes in an iterative dialogue between data and literature (Tavory & Timmermans, 2014). As a result of the abductive analysis, the original frameworks were elaborated in the sense that they were successfully used in the analysis of a new data sample, and the new findings thus elaborate the underlying theory. In the case of a constructive-interpretative and pragmatic philosophical paradigm, theory means interpretive sensemaking and contextual explanation (Welsch et al., 2011). In the first three articles, the focus was on multiple different organizations in the network and their innovation activities.

The data for Article IV were analyzed inductively without a pre-determined analysis framework, meaning that the codes and themes emerged from the data but acknowledging that my previous knowledge as a researcher influenced the emerging codes. This approach is more on the inductive end of the scale, and the abduction was kind of "hidden," as in most analyses (Tavory & Timmermans, 2014). Here, the focal organizations of the analysis were the two large product owner organizations, but the analysis intentionally covered other organizations as part of the networks to generate new knowledge about value chain adoption.

The main analysis method in the articles for this dissertation was thematic analysis, defined as subjective interpretation of the data in text, voice, or video format through more or less systematic coding, seeking to understand the meaning with the help of the codes within their context (Joffe & Yardley, 2004).

In the qualitative thematic analysis, I identified two appealing perspectives–interpretative and systematic protocol-like. These both contain their own assumptions about the nature of the informants and how the analysis takes place. In interpretative perspectives (van Maanen, 1979), the informants may be misleading (intentionally or accidentally, per their bounded rationality), and the task of the researcher is to interpret what is meaningful from the data. In this way, the analysis is highly iterative and potentially non-convergent. The analysis process goes from first-order codes to understand to second-order codes to explain (in iteration) and aims to provide a holistic narrative of what is actually happening. In the systematic protocol-like approach, in the so-called Gioia method (Gioia et al., 2013), the informants know best, and that is not to be questioned. Interpretation is based on information given by informants and follows a sequential protocol, where the level of abstraction grows and findings seem to aggregate into convergence.

In my work, I utilized both of the perspectives I identified. While in the first three articles the systematic protocol-like analysis was visible up front, I had the interpretative analysis in the background in my thinking when conducting the analysis. In this way, I utilized a categorizing strategy to label and group the main findings (Maxwell, 2012). In the fourth article, an interpretative approach was more guiding, but the systematic protocol-like approach provided a means to start the analysis and arrive at a mid-research understanding. In this way, I utilized a connection strategy of analysis to identify the key relationships that tie the events together by means of an analytical narrative (Maxwell, 2012).

Coding the data means, in its simplicity, organizing the structure in which theoretical reflectivity happens (Gordon-Finlayson, 2010), or, in other words, sorting the meaningful evidence in the data into aggregate categories. The coding strategies used were guided by the previously mentioned approaches and research questions in each article, meaning that the research aim inspired a set of questions about what to look for in the data, and the coding type was selected based on the needs of the research, as suggested by Saldaña (2012). In the analyses, I utilized a combination of different coding strategies, including initial coding, pattern coding, focused coding, elaborative coding, process coding, and structural coding (Saldaña, 2012).

As a more philosophical note about data analysis, data collection and data analysis are not separate phases in qualitative research. The analysis has already started after the first encounter with the data in the early phase of data collection—especially if the researcher collecting the data is also conducting the analyses (Tavory & Timmermans, 2014), as is the case for the articles in this dissertation.

Finally, after the data analysis, it was time to interpret the findings and draw conclusions from them. In the quest to make sense of the findings, several different means were used. The findings were visualized by drawing figures and creating tables, which helped in noting patterns and themes, clustering notions, and making contrasts and comparisons, as suggested by Miles et al. (2014). Simultaneously, the conclusions were reflected together with earlier research. This way, the conclusions could be drawn and the reasoning walked through with the coauthor of the articles.

4 FINDINGS

4.1 Adopting additive manufacturing in SMEs: Exploring the challenges and solutions

4.1.1 Rationale and positioning

At the time of planning the study for Article I, AM was not yet being adopted by numerous companies for industrial use. However, there was growing interest in trying out the technology. Prior research has identified this dilemma as well. Flores Ituarte et al. (2016) noted that AM technologies have not been adopted in the supply chains of manufacturing companies. Ortt (2016) noted that although AM technologies have been around for over three decades, academic research focusing on business and supply chains has only recently begun. Despite the slow adoption of AM, a growing number of studies have started to show the potential benefits of AM for business in general (Oettmeier & Hofmann, 2016; Steenhuis & Pretorius, 2017), for supply chains and supply chain innovations (Holmström et al., 2010; Holmström & Partanen, 2014; Weller et al., 2015), and for providing solutions for more sustainable manufacturing (Beltagui et al., 2020; Ford & Despeisse, 2016).

Previous research on the challenges and barriers of AM adoption has focused on single companies or on a mix of smaller and larger companies. The identified gap and need were to include a more diverse set of small and medium-sized enterprises (SMEs) in particular, from the early phase of AM adoption to the study. Motivated by the need to promote promising new manufacturing technology and the gaps identified from previous literature, the following research question were formulated:

1. How do SMEs in different supply chain positions differ in their challenges in adopting AM?
2. How can SMEs overcome the challenges?

Regarding this dissertation, Article I focuses on the early adoption of AM and the intention to adopt AM to study the challenges and barriers that hinder adoption and the means of overcoming these challenges.

4.1.2 Findings of Article I

Adopting AM was considered challenging among the SMEs that participated in the study. These SMEs are part of the supply chains of larger firms. The findings of this study generate new insights and knowledge about the challenges experienced before or during the adoption of AM and the actions required to overcome these challenges. Figure 3 illustrates the findings of this study.

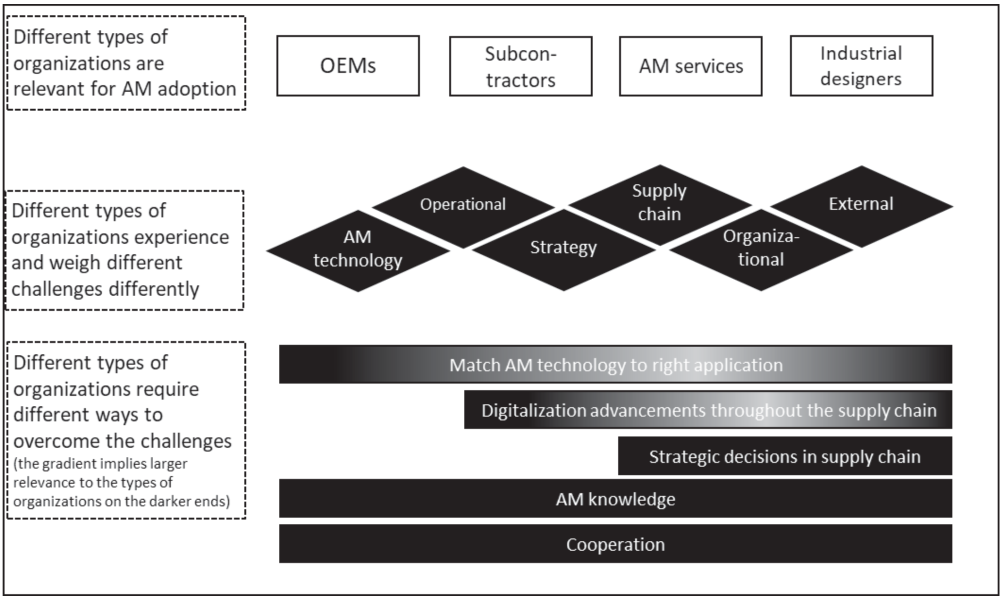

Figure 3. Findings of Article I

The 33 identified challenges were divided into 6 categories: technology-related, strategic, supply chain-related, operational, organizational, and external challenges. Technology-related challenges were divided inconsistently depending on the type of company (and supply chain position), and this was also linked to the knowledge that these companies had about AM and related to their focus on operations and supply chain position. Strategy-related challenges were most often emphasized by contract manufacturers and OEMs (Original Equipment Manufacturers), highlighting the yet-to-be-developed supply chains for AM.

As a way to overcome challenges, OEMs and industrial designers highlighted that AM technology and processes need to advance and that the right application needs to be found for AM manufacturing. Subcontractors and industrial designers highlighted that they need digitalization advances to promote AM adoption, since they are both lacking these as well as seeing the need in the whole supply chain from their viewpoint. Industrial designers and AM service providers stated that other companies in their network need strategic decision making to initiate AM adoption. All types of companies stressed the need for new, specific knowledge about AM to support AM adoption. Interorganizational collaboration was suggested to share knowledge about AM as well as to share the different manufacturing capacities of different companies over their (existing or emerging) network, as most of the SMEs cannot compete on the AM market with their own resources alone.

4.1.3 Contribution of Article I

Article I expanded the focus of AM adoption to supply chain-level issues. The analysis in Article I revealed that different types of companies are relevant for AM adoption, but there might be variations in the positions and tasks that they undertake in the supply chain that adopts AM. This is also apparent in how the perceived challenges were experienced by different types of companies when they intended to adopt AM or when they were in a very early phase of adoption. Interorganizational collaboration is highlighted in terms of acknowledging the differences and relevance of different types of companies in AM adoption, and this contribution is novel, as previous research was focused on early adopters and straightforward supplier–customer relationships (Flores Ituarte et al., 2016; Mellor et al., 2014; Oettmeier & Hofmann, 2016; Rylands et al., 2016) and provides further evidence on the challenging nature of adopting AM in the study industry context.

Article I concluded that it was not self-evident which companies should be the ones to own AM machines. Furthermore, companies experience different adoption challenges with regard to their company characteristics and supply chain position. Technologies in general influence the value chain, so this is the case with AM. Therefore, the manufacturing innovations of AM have to be diffused widely in the value chain to start being worth adopting, and this supports the findings of Steenhuis and Pretorius (2017) and Muir and Haddud (2018). The supply chain-wide setting of AM adoption may pose a major barrier to diffusing AM in the industry. To overcome this notable barrier, the systemic nature of AM technology innovations must be acknowledged, meaning that SMEs and large firms cannot develop their AM capabilities in isolation.

As a highlight of the findings regarding overcoming adoption challenges and barriers, interorganizational cooperation was identified as one possible key solution, which supports the propositions of earlier studies by Oettmeier and Hofmann (2016), and Deradjat and Minshall (2017). In conclusion, the SME as a promotor of

AM technology, in any of the supply chain positions, has to cooperate with lead customers and innovate new kinds of products to demonstrate the benefits and value of AM in order to create demand for AM.

4.2 Supply chain innovations for additive manufacturing

4.2.1 Rationale and positioning

Article II built on ideas that emerged during the initial research for Article I, especially on the idea of the systemic nature of AM adoption that should concern the entire supply chains or networks. The purpose was to understand in-depth the emerging AM-related supply chain process and map it. This paper explored supply chain innovations triggered by the introduction of AM to the supply chain. The goal was to generate new insight and knowledge about how different companies in different supply chain processes view the adoption of AM into their supply chain and the supply chain innovations needed to start comprehensively leveraging the benefits of AM. The level of analysis in this study is interorganizational, and the units of analysis are internal company processes and interorganizational processes.

The literature review revealed that the majority of previous studies had focused more on single early AM adopters, which were mostly large companies in consumer goods industries. Out of those previous studies, only a handful had considered supply chain-level issues (Oettmeier & Hofmann, 2016; Rogers et al., 2016; Rylands et al., 2016; Thomas, 2016), but from the perspective of a single company. Based on this, a research gap was identified: AM adoption studied from the broader perspective of the supply chain. The following research questions were formulated:

1. What kinds of contextual changes take place in business-to-business AM supply chains?
2. How—through what kinds of activities—do different firms participate in the AM supply chain process?
3. How can firms leverage AM through innovations in their supply chains?

4.2.2 Findings of Article II

The findings revealed that three out of four large companies in the dataset had replaced some of their products with AM products. However, most respondents stated that traditional manufacturing is still dominant, but AM is constantly more visible through specialized AM firms in their network. Regarding AM and changes in the supply chain, this study revealed specific supply chain-level changes that had started to take place and were estimated to be important in the future. These are: digitalization of the entire design-to-manufacturing chain, which increases the need for trusted partners; AM leading to changes in operations management and complementing traditional manufacturing and, eventually, leading to changes in the supply network structure and logistics requirements.

By purposively choosing different types of companies acquainted with AM, the analysis provided an understanding for constructing a metallic AM supply chain process illustration. This process illustration shows that AM requires more design work than traditional manufacturing. Compared to traditional manufacturing, AM supply chain processes have the potential to reduce warehousing processes if the operation model is produced only based on need. Then again, AM also requires an extra step in the raw material manufacturing phase (especially when using powder bed metallic AM), as well as post-production and quality assurance phases (although much research is going on to reduce these steps). This analysis also shows that, in the emerging new AM supply chain, different types of companies participate differently and have different task orientations in the different parts of AM supply chain processes.

Distinct patterns arise, as summarized in Figure 4. First, different companies participate during the same phase of the supply chain process. Here, collaboration within a phase occurs. Second, a certain pattern of participation and major tasks taken across the phases of the supply chain process emerges. This shows the sequential participation and task orientation of different types of companies and the collaboration needs throughout the supply chain.

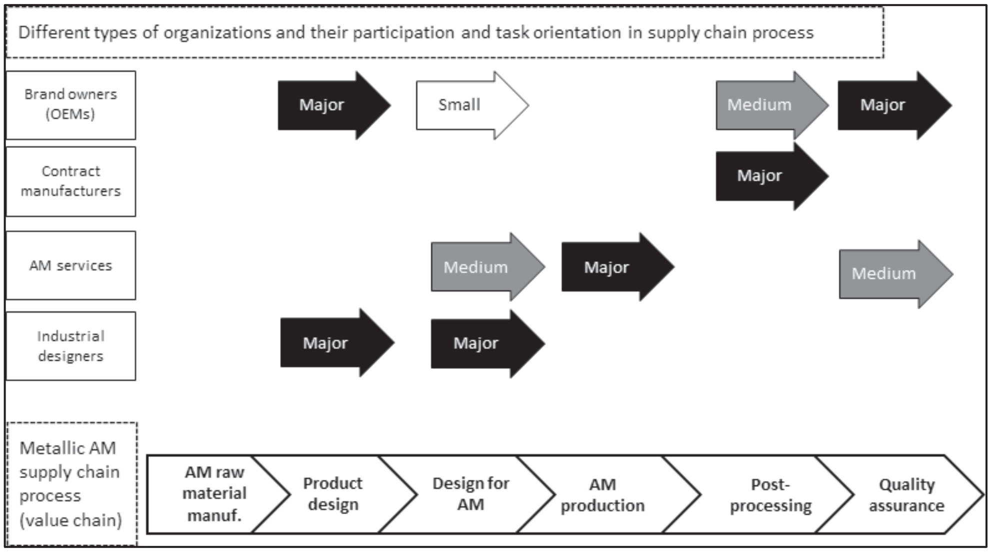

Figure 4. Findings of Article II

For the adoption of AM, complementary innovations are needed throughout the supply chain. These supply chain-level innovations occur in different parts of the AM supply chain and partially concern different companies. Product innovations needed in the early phase of the AM supply chain are a concern for brand (product) owners and AM skilled industrial designers. Innovations in customer/supplier relationship management, for example, in the form of new tools for quality management and quality documentation requested by the customer, developed together with the customer, AM producer, and supplier, are required at the end of supply chain, but need to be operational from early on. Digital systems throughout the entire design-to-manufacturing chain need innovations and investments to support AM. Finally, partnership and collaboration are needed to share knowledge and create opportunities for the supply chain and operations management to benefit from AM possibilities. These findings support the conclusion made in Article I about AM as a systemic innovation.

4.2.3 Contribution of Article II

The findings of Article II show that in industrial business-to-business supply chains, the AM-associated transformation of supply chains is complex and implies that new kinds of companies with new kinds of tasks, new materials, and new digital information flows are relevant. The findings from Article II offer a contrasting view to the previous AM supply chain-related studies (Campbell et al., 2011; Holmström et al., 2010; Holmström & Partanen, 2014) that conceptualize AM as a means to simplify supply chains or improve their efficiency. The findings in Article II lend support to arguments by Steenhuis and Pretorius (2017) that AM has the potential for wide-scale applicability with different types of innovations (incremental and radical), and the potential utilization paths are complex.

The findings of this study explicate that AM is a concern for more than just a single company in the supply chain, and that AM is not an isolated manufacturing technology innovation that one company can adopt and benefit from. Within phase and along phase, interorganizational collaboration is revealed within the supply chain. These findings contribute and add to previous studies about AM supply chain level indications (Oettmeier & Hofmann, 2016; Rogers et al., 2016; Rylands et al., 2016; Thomas, 2016).

From the findings of this article, some conceptual expectations arose from the analysis that support the findings from Article I. It seemed increasingly clear at this point that AM should be treated as a systemic innovation. Systemic innovation needs, compared to isolated innovations needs, require complementary innovations to realize their benefits and value at full scale (Chesbrough & Teece, 2002). This was apparent in the analysis by informants (especially among SMEs) emphasizing that a collaborative approach could be seen as a means of benefiting from AM-driven changes, and this supports Oettmeier and Hofmann's (2017) predictions.

4.3 Additive manufacturing innovations: Stakeholders' influence in enhancing sustainability and responsibility

4.3.1 Rationale and positioning

The research idea for Article III builds on findings from Articles I and II about collaboration between several organizations and how innovations are especially relevant in the context of AM adoption. The focus is furthermore expanded to study which other relevant organizations–in other words, stakeholders–would be involved, as previous research suggested that AM innovations do not happen in isolation (Freeman et al., 2010; Pagell & Shevchenko, 2014). Furthermore, the sustainability and responsibility of AM innovations were emphasized in the research project where the industry expert informants and I were working. This was the motivation to study whether stakeholders influence AM innovations.

Previous studies have recognized that AM could potentially become one solution for more sustainable manufacturing (Beltagui et al., 2020; Ford & Despeisse, 2016) to support the increasing need for more sustainable and responsible innovations. To systematically create new innovations, companies need a systematic innovation process (Drucker, 1985), which would also include the relevant stakeholders with different interests (Freeman et al., 2010). Previous research related to sustainable innovations has identified that external stakeholders are especially relevant for companies that aim for sustainable and responsible innovations to support and guide the innovation process, and in general, external stakeholders have varying amounts of power to influence the innovation process to enhance the sustainability and responsibility of AM innovations by means of different types of mechanisms (Berger et al., 2004; Pagell & Shevchenko, 2014).

The stakeholder view was used in theorizing this study (Freeman et al., 2010). Earlier studies had already recognized some relevant stakeholders as part of their studies (Koch, 2017; Monzón et al., 2015; Rylands et al., 2016). Previous studies have shown that there are signs that stakeholders are relevant for AM innovations, but there has not been a systematic attempt to map the stakeholders or study their influence on AM innovation. The following research question was formulated:

> How do different stakeholders influence AM innovation activities in relation to companies in the AM supply chain to enhance the sustainability and responsibility of AM innovations?

4.3.2 Findings of Article III

The relevant activity-oriented supply chain was first constructed based on the informants' views of their operations. This formed the supply chain of primary stakeholders. The primary stakeholders in this study were those other organizations that had a direct link to the AM supply chain; in other words, they had a business interest in AM innovations. These primary stakeholders were settled in the following main categories: AM raw materials provider, AM designer, software developer, AM machine manufacturer, AM producer, and AM products customer. These primary stakeholders were the focal companies developing AM innovations (AM machine, process, and product innovations) aiming for market introduction and are illustrated in the center of Figure 5.

The external stakeholders were identified, and their participation in the organization's innovation activities was analyzed. External stakeholders are defined as organizations that have an interest in or contribute to AM but are not key actors in the direct market-oriented AM supply chain. These external stakeholders were the following: governmental organizations (regulators), NGOs, funding organizations, training organizations, research and technology organizations, standardization organizations, patent organizations, trade associations, organizations representing customers and end users, and insurance companies. These are placed around the focal companies in Figure 5.

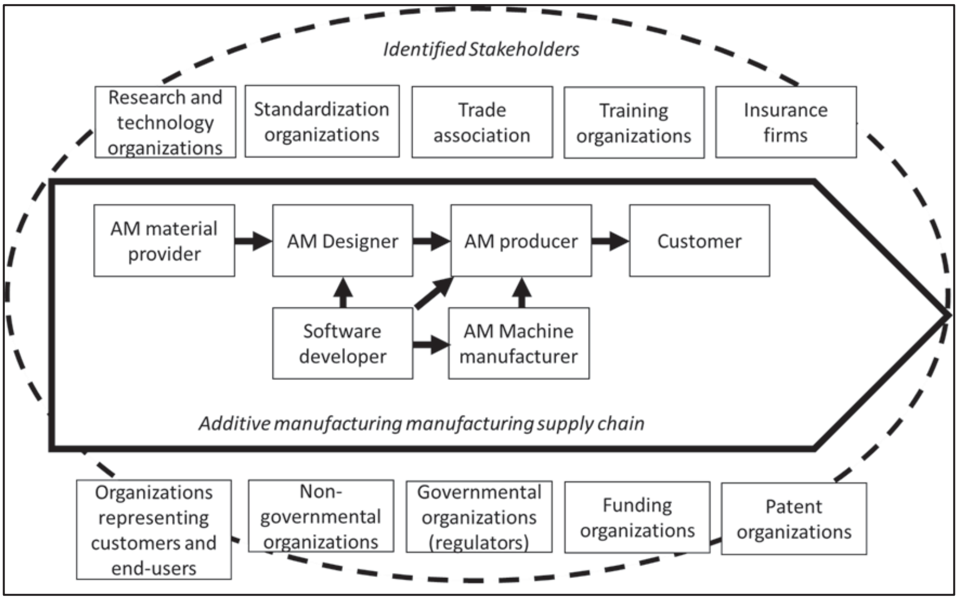

Figure 5. Findings of Article III, stakeholder identification

The findings show that these different external stakeholders influence the AM innovation process of firms in AM supply chains in the following ways:

- Stakeholder participation may be reactive when AM companies seek external support and the stakeholder's power is weak, meaning that their advice or involvement is voluntary from the perspective of the innovating company.
- Stakeholder involvement can be very active but can lack power; it is intended to help the innovation succeed or to foster sustainability or responsibility.
- Stakeholder participation can be very active and powerful, meaning that companies need to comply with everything that the stakeholder advises (in this case, lack of compliance would usually greatly endanger the success of the innovations).

- Stakeholder involvement is low but powerful, and it sets sustainability- and responsibility-related pressure (for example, non-compliance would be against laws and regulations).

In addition, the interest and power of secondary stakeholders influence the sustainability and responsibility of innovations through mechanisms of fostering or setting pressure to meet the requirements. It is also notable that the power and interest of stakeholders, as well as their mechanisms of influence, vary depending on the phase of innovation, whether the innovation process is in its early phase, the development phase, or the phase of diffusing the innovation to markets.

4.3.3 Contribution of Article III

Ten external stakeholders relevant to AM innovations were identified. This study expands the understanding and knowledge about AM stakeholders, as previous studies regarding stakeholder involvement in AM innovation processes are limited. The findings are in line with the limited number of previous studies, concluding that training organizations and research organizations are important (in line with Rylands et al., 2016). The findings also illustrate that standardization organizations have an influence during the AM innovation process and that engineering associations are important hubs of knowledge and ideas. These findings lend support to earlier findings by Monzón et al. (2015) and Koch (2017).

Interorganizational collaboration through influence emerged from the findings. The findings show that there are external stakeholders without an economic interest in the supply chain that can contribute to the sustainability and responsibility of innovations, as suggested by Pagell and Shevchenko (2014). This study further adds to Rylands et al. (2016) by identifying that training can be a good way to educate AM companies in areas that support AM adoption.

Finally, the findings of Article III contribute to the limited previous research by adding the perhaps neglected perspective of external stakeholders' influence on the AM innovation process, especially concerning sustainability and responsibility. The relational power and interests of the 11 identified external stakeholders were analyzed throughout the innovation process phases. This was done by analyzing each of the three innovation process phases–idea generation, development, and diffusion–combining the stakeholder mapping (Bryson, 2004) and influence mechanisms (Meixell & Luoma, 2015) with the framework of the three phases of the innovation process (Hansen & Birkinshaw, 2007). This combination of different analysis methods is also a contribution to stakeholder theory (Freeman et al., 2010).

4.4 Additive manufacturing value chain adoption

4.4.1 Rationale and positioning

Previous research indicated that the process of AM adoption potentially spans the value chain instead of being limited to a single company (Steenhuis & Pretorius, 2017). However, in the previous articles (especially in Articles I and II), there were not yet specific adoption cases or, more precisely, those companies that had them did not want to share them. The planning for Article IV started when a couple of companies expressed that they would be willing to share their experiences about the organizational adoption of AM. These cases provided a situation for a study in which many companies were involved. After negotiations, research access was settled, and two different cases (the second having two sub-cases) were established.

Earlier research has shown that manufacturing companies have different possibilities for adopting AM (products). Adoption can occur by directly purchasing AM-manufactured products or by investing in AM machines and producing AM products internally (Oettmeier & Hofmann, 2016). However, as shown in Article II of this dissertation, organizations can participate in research and development projects and then contract manufacture AM components through a new or existing supply chain. The initial idea behind Article IV was to study cases where the adopting companies did not themselves invest in AM machines, but where the adoption of AM took place in an interorganizational setting. The following research question was therefore formulated:

How and why do companies adopt AM in their production value chains?

4.4.2 Findings of Article IV

The findings from Article IV reveal that the innovation projects under study were pro-actively marketed by an AM industrial design company that had acquired an understanding about this new manufacturing technology. At the same time, the companies with their own products, and to which the industrial designers marketed their services, had accumulated an initial interest in AM through participating in training at universities or through internal investigations.

A distinct process consisting of sequential activities during the innovation project (also potentially having feedback loops) was identified and is presented in Figure 6. In this process, AM adoption starts by initiating collaborations with different types of companies that possess different types of complementary knowledge. During the process, new values were created through product and process innovation, and these were analyzed in depth. Additive manufacturing added value was considered one of the key factors of successful AM innovation and was therefore significantly influential in the success of adoption. By adopting AM, value chain costs, availability, functionality, and quality were the areas where AM added value.

Finally, the network structures throughout the innovation project were mapped, and the changes in the value chains became visible. In each case, a preexisting supply chain set up for ordinary supply and manufacturing was already in place. However, in the two sub-cases, the value chain became obsolete. After the cooperative AM innovation project, the old value chain was discontinued, and a new value chain was established. This finding shows the central position of the industrial designer company as the change driver and value chain organizer, and the participation of other companies became evident as well. Figure 6 highlights the main findings and how they relate to each other (curved arrows connect different perspectives).

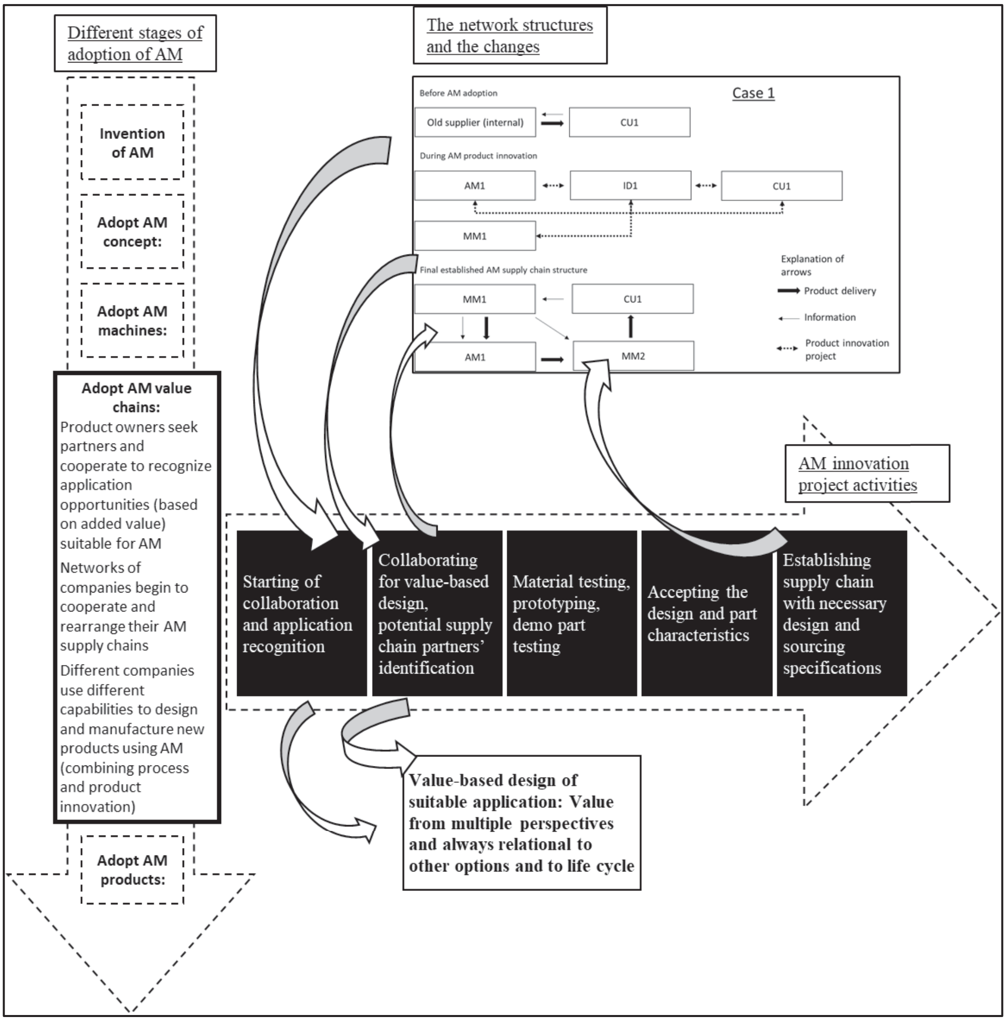

Figure 6. Findings of Article IV; curved arrows connect different analysis illustrations together

4.4.3 Contribution of Article IV

The findings and contribution from Article IV elaborate and further extend the theoretical understanding of the process of AM technology adoption. A completely new stage of AM value chain adoption is suggested to advance the understanding of the existing framework of AM adoption by Steenhuis et al. (2020). For large-scale AM adoption, and in cases where the location of AM machines in the value chain is not self-evident (as found in Article II), the concept of AM, AM products, and processes need to be adopted at the value chain level.

The findings of Article IV show evidence that AM adoption is a process where the right applications have to be recognized, the products and processes have to be developed, and new value chains have to be established. Active forms of interorganizational collaboration are highlighted in the findings, in which the different knowledge and skills of participating collaborators can enhance the success of AM value chain adoption. The findings further show that application recognition and re-design of the product and process are fundamental stages for successful AM value chain adoption so that AM adds value from a technical and/or business perspective. The findings show how AM added value compared to the alternatives from the perspectives of cost, functionality, quality, and availability.

Besides technical and business value, this value-driven design was also influenced by and toward sustainability. This finding shows that incorporating value-driven application recognition and design enables sustainability aspects to be taken into consideration, as suggested by Holmström et al. (2017) and Ott et al. (2019).

5 DISCUSSION

This chapter synthesizes the findings of this dissertation regarding the research questions and discusses the synthesized findings in light of earlier research. Section 5.1 focuses on the discussion and answers the first sub-question, "How do organizations manage the adoption of additive manufacturing in their interorganizational networks?". Section 5.2 focuses on the discussion and on answering the second sub-question "How do organizations address sustainability in AM innovations?".

Section 5.3 answers the main research question, "How, through what kind of an innovation adoption process, do organizations adopt AM?". The section then further discusses the contributions of this dissertation to more generic technology innovation adoption theories. Although interesting on its own, AM can be seen as a specific context of systemic manufacturing innovation adoption. Therefore, the potential elaborations of more generic theories are discussed.

5.1 How do organizations manage the adoption of additive manufacturing in their interorganizational networks?

Based on the findings of this dissertation, multiple perspectives are relevant when organizations manage the adoption of AM in interorganizational networks. To manage AM adoption, organizations need to understand the different types of organizations relevant to AM adoption and their specific needs and challenges. These different types of organizations contribute to emerging AM value chains by performing different tasks at different positions. It is necessary to understand the relationship between AM as a manufacturing innovation and the goods or processes that are both enabled and required for successful AM value chain adoption. Thus, it is necessary to identify and/or develop the new value that AM adds for AM value chains to become feasible to adopt.

The findings of the first two articles (which Articles III and IV expand upon) bring the focus of AM adoption to the supply/value chain level. The relevance of different types of companies and their involvement in AM adoption is evident. These findings offer the insight that, in addition to multiple actors being relevant, different measures need to be taken when managing the adoption of AM, since there are differences in their adoption challenges. This finding adds to previous AM adoption research, as most earlier AM studies have focused on single adopter companies or straightforward supplier–customer relationships (Flores Ituarte et al., 2016; Mellor et al., 2014; Oettmeier & Hofmann, 2016; Rylands et al., 2016). Furthermore, this finding offers evidence to support the expectation that multiple types of organizations are relevant in AM adoption (Muir & Haddud, 2018; Oettmeier & Hofmann, 2017; Steenhuis & Pretorius, 2017). This finding is also supported by previous research that has discussed the relevance of the participation of other organizations in the value chain in technology adoption in general (Arvanitis & Hollenstein, 2001; Linton, 2002; Tyre, 1991).

Additive manufacturing adoption imposes a systemic change to the value chains of the adopting interorganizational networks, as similarly noted by Tyre (1991) with regard to advanced manufacturing technology in general. A full innovation project to identify and design the right application was established in the cases of Article IV to overcome perhaps the most relevant AM adoption barrier (recognized in Article I). The identified and developed new value that AM added was instrumental in the AM adoption process. Previous AM-related studies have shown that AM enables new value (Fontana et al., 2019) and that this new value is linked to AM adoption (Rylands et al., 2016), but not to the extent indicated by the findings of this dissertation.

Adoption of AM and the relation of its consequent possibility to create further (product or process) innovations seems to be connected to the successful adoption of AM. Previous research has studied the possibilities where AM could provide a straightforward substitute for traditional manufacturing, for example, in mass customized production (Oettmeier & Hofmann, 2017). This dissertation argues that in many cases, it is about the new kinds of products (through value-added thinking) that make it worthwhile to introduce AM. The relationship between technology adoption and new innovations has been identified as holding at a generic level (Liu et al., 2017). This further motivates organizations to view AM from multiple viewpoints and to consider AM value chain adoption when planning to introduce AM to their networks.

Additive manufacturing innovation projects were carried out in an interorganizational setting, where a company with less knowledge about AM leveraged the knowledge of other companies and combined it with proprietary knowledge to create new product innovations where AM added value. This kind of interorganizational collaboration on innovations has been identified as a possible way to innovate (Chesbrough, 2003; Van de Ven, 2004). This seems to be a valid option to overcome both the knowledge and application recognition barriers of AM adoption, supporting the expectations and early findings by Oettmeier & Hofmann (2016), Rogers et al. (2016), Rylands et al. (2016), and Thomas (2016).

Secondary stakeholders can provide support for the AM innovation processes necessary for AM adoption, as Article III shows by expanding the view of supply chains to the stakeholder level. This indicates that, in addition to direct collaboration, a more subtle form of interorganizational collaboration is relevant. The support of stakeholders is also relevant when overcoming the challenges and supply chain change requirements that were raised in Articles I and II. There are limited previous studies regarding stakeholder involvement in AM innovation processes. Training organizations and research organizations are shown to be important based on the findings of this dissertation, which is in line with Rylands et al. (2016) and Maresch and Gartner (2020). Also, standardization organizations have an influence during the AM innovation process, and engineering associations are important hubs of knowledge and ideas. These findings lend support to the earlier findings of Monzón et al. (2015), Koch (2017), and Stentoft et al. (2021).

Systemic manufacturing technology innovations such as AM cannot be seen as isolated innovations that could be leveraged merely as a technology adoption task, but there is a need to study AM adoption from a wider organizational perspective and from multiple levels (company and networks, innovation and operations). The AM-associated transformation of supply chains due to AM value chain adoption is complex and implies that new kinds of companies with new kinds of task orientations are relevant, along with new material and digital information flows. The findings thereby offer a contrasting view to previous AM supply-chain-related studies (Campbell et al., 2011; Holmström et al., 2010; Holmström & Partanen, 2014) that conceptualize AM as a means to simplify supply chains or improve their efficiency.

Based on these findings, it can be concluded that the benefits of AM on a large scale will be achieved only if the broader interorganizational network adopts AM technology. The findings imply that there is a need to understand AM adoption as a shared concern and systemic manufacturing innovation adoption at the level of the whole supply chain instead of seeing it as a firm-specific implementation task. These findings lend support to arguments by Steenhuis and Pretorius (2017) that AM has the potential for wide-scale applicability with different types of innovations (incremental and radical), and the potential utilization paths are complex.

5.2 How do organizations address sustainability in AM innovations?

Based on the findings of this dissertation, organizations can address environmental and social sustainability (and responsibility) in AM innovations by focusing on value-adding design for new AM innovations and by actively seeking support from stakeholders (both primary and secondary). These findings, therefore, provide a small but relevant contribution to this topic.

Incorporating value-driven application recognition and design enables environmental sustainability aspects to be taken into consideration. Besides technical and business value in value-driven design (discussed in 5.1), Article IV revealed that AM innovations are influenced by and toward sustainability. Behind the traditional value drivers, the companies in the case studies wanted to secure the availability of spare parts to prolong their vehicles' life cycles, which would contribute to the sustainability of their operations. The need to view the full life cycle of AM products to see the sustainability outcomes has been identified in previous studies but on a more conceptual level (Kritzinger et al., 2018; Maresch & Gartner, 2020; Niaki & Nonino, 2018; Ott et al., 2019), as well as in production innovation literature (Larsson, 2020; Säfsten et al., 2022).

Even though Article IV did not specifically analyze sustainability, during the secondary analysis for this dissertation the sustainability perspective became evident. Article IV revealed that being able to visualize the full life cycle is necessary as companies want to see the value through the full value chain, and this contributes here is the opportunity to evaluate sustainability aspects. The relevant value drivers for supporting AM adoption and for supporting a sustainable direction of development need to be identified by each organization in the network. In the other case of Article IV, the technical efficiency of the new AM component contributed to the energy efficiency of their processes, which directly relates to sustainability. Therefore, by showing evidence of the need to consider value chains simultaneously with product innovations and added value, these findings contribute to earlier research on application selection and value-driven innovation in AM (Ballardini et al., 2018; Fontana et al., 2019; Rylands et al., 2016). Some studies frame this kind of sustainability into economic sustainability as these innovations are lowering the costs or improving performance (Niaki et al., 2019a; Niaki et al., 2019b Niaki & Nonino, 2018). However, based on the arguments of many authors, the future focus should be more on environmental and social sustainability of innovations, because economic aspects are embedded in innovations as a status quo and there is no need to highlight them (de Figueiredo & Marquesan, 2022; Dyck & Silvestre, 2018; Owen & Pansera, 2019; Säfsten et al., 2022). Economic performance embeddedness was also evident from the findings and the discussion in chapter 5.1 in AM adoption process, and therefore this chapter provides another point-of-view for AM adoption from the perspective of sustainability.

Based on the three categories of sustainable innovations–sustainability-relevant innovations, sustainability-informed innovations, and sustainability-driven innovations (Calabrese et al., 2018; Hansen & Grosse-Dunker, 2013; Jay & Gerand, 2015; Klewitz & Hansen 2014)—AM innovations fall into the categories of sustainability-relevant and sustainability-informed innovations. This means that the outcomes (AM innovations) are less harmful than the alternatives.

Organizations can address the environmental and social sustainability of innovations by actively seeking and accepting support and guidance from stakeholders. The differences in stakeholders throughout the innovation processes (both in Article III and IV) demonstrate the complexity of innovation networks and the nuances of multiple different stakeholders who potentially have an influence on the AM innovation process to enhance environmental and social sustainability by either fostering (i.e., providing knowledge about potential value drivers for sustainability) or by regulating (i.e., providing guidelines to follow). This finding adds to the findings of Rylands et al. (2016) and Maresch and Gartner (2020) by indicating that training might be a useful tool for educating AM firms about sustainability. This is also relevant when the value that AM can add is discovered through interorganizational cooperation, as also argued by Rahmana et al. (2022). The stakeholders use their influence to foster the sustainability and responsibility aspects of the innovation processes, adding pressure to them, or giving general support for the innovations to be successful. Interestingly, the power, interests, and influencing mechanisms of stakeholders seem to be dynamic, meaning that the same stakeholder may take a different approach depending on the innovation process phase. The findings and analysis framework of Article III therefore provide AM organizations a way to identify the central stakeholders, promote market access, and add sustainability and responsibility aspects to their innovations.

Finally, sustainability in the manufacturing sector can be viewed during different phases: raw materials manufacturing, manufacturing, and using the manufactured goods. As this dissertation had a product innovation focus, the sustainability focus was also on the phase of using AM-manufactured goods. However, it is acknowledged that potentially a large part of AM sustainability may stem from consuming fewer resources (raw material and/or energy) during the manufacturing process compared to using alternative manufacturing methods (Berman, 2012; Chen et al., 2015; Gao et al., 2015; Gebler et al., 2014; Holmström & Partanen, 2014). Although this did not emerge from this dissertation, it may become much more relevant to acknowledge in future AM innovations.

5.3 How, through what kind of an innovation adoption process, do organizations adopt AM?

The findings of this dissertation indicate that AM is a systemic manufacturing innovation when it is adopted, and thus, the innovation adoption process of AM in organizations is a systemic manufacturing innovation adoption process. Systemic innovation means that the underlying (technology) innovation only becomes beneficial when coupled with complementary innovations (Chesbrough & Teece, 2002; Mulgan & Leadbeater, 2013; Takey & Carvalho, 2016). Complementary innovation most often comes in the form of product innovations, since without the 'product', manufacturing technology is of no use. Since AM is so distinct from traditional manufacturing concepts, basically every product that is to be manufactured with AM requires some degree of innovation, at least in the form of an incremental redesign for AM manufacturability.

This dissertation provides a novel finding in the theoretical understanding of systemic manufacturing innovation adoption. The interconnection and synchronous relationship between technology adoption and innovation creation has been identified at the generic level of innovation (Liu et al., 2017), but not specifically in the context of advanced manufacturing technology innovation. Although there are a number of studies that focus on advanced manufacturing adoption, the technology is often categorized as complex to adopt and is downplayed as one factor, among others, to explain success (Linton, 2002), and the relationship with products is from the perspective of production optimization (Rogers, 1962, 2003; Yamamoto & Bellgran, 2013).

Complementary innovations, however, do not stay at the level of product innovations but may be expanded into process innovations that may involve restructuring the whole supply chain. The supply chain structure may need to be changed if AM is to be adopted. Supply chain flexibility, or, for example, establishing a new supply chain to replace an obsolete supply chain, may come into question when supply chain innovations are coupled with AM and AM product innovations.

This dissertation argues that eventually these simultaneously or closely sequential complementary innovations may generate a whole new value chain that needs to be adopted by every organization involved in the network. Naturally the "what" is adopted, and "to what extent" it is adopted depends on the positions and tasks of an organization in the network (Maula et al., 2006). These findings complement the findings of Liu et al. (2017) and contribute to the research need to address the specialties of systemic manufacturing innovation adoption (Larsson, 2020; Larsson & Karlsson, 2019; Tyre, 1991).

This dissertation thus adds to mainstream technology innovation adoption theories that focus on autonomous innovations that are feasible on their own (Clark, 1987; Davis, 1989; Mansfield, 1993; Milgrom & Roberts, 1990; Rogers, 1962, 2003; Tornatzky & Fleischer, 1990). Figure 7 illustrates how the findings of this dissertation elaborate the technology adoption process model of Tornatzky and Fleischer, 1990 (similar to Rogers, 1962, 2003). In Figure 7, the left side is modified from Tornatzky and Fleischer (1990), and the right side is the new contextual elaboration of this model of how adopting systemic manufacturing innovations adds another process (a loop with feedback loops to the existing model). The small arrows show the more complex process flows between complementary innovations and AM (underlying systemic manufacturing innovation) adoption.

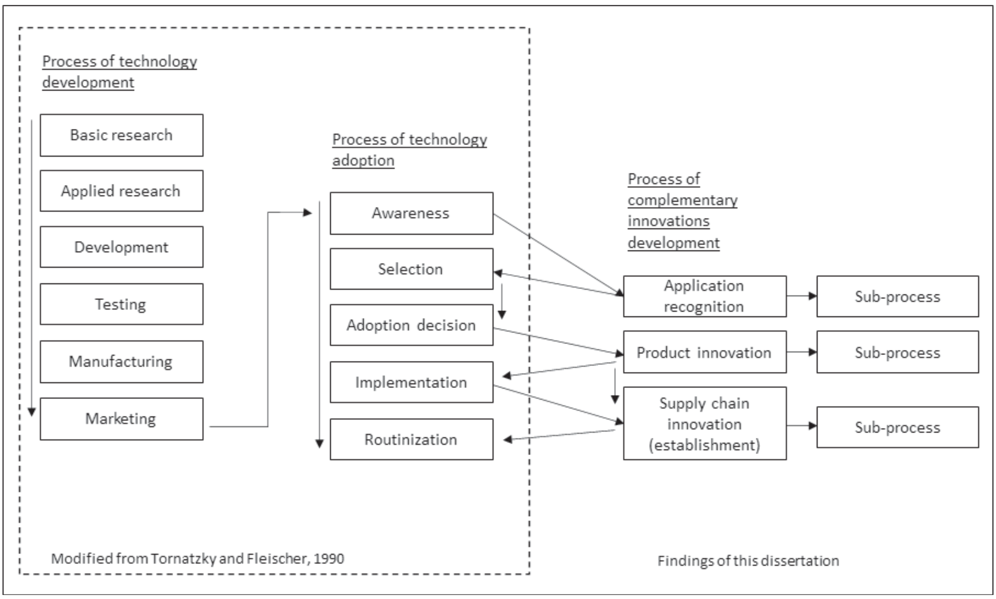

Figure 7. Findings of this dissertation to elaborate on the existing innovation adoption process model

The adoption of a systemic manufacturing innovation and its requirement for complementary innovations also have implications for an interorganizational collaboration perspective. Particularly in the early phase of AM diffusion (emergence of a new industrial field), knowledge about AM is unevenly distributed among the organizations relevant to AM innovations and adoption. Further, the technological capacities (i.e., design software and AM machines) are unevenly distributed across the network of organizations relevant to AM innovations and adoption. To overcome these barriers, interorganizational collaboration is one way to make use of scattered knowledge and capacities to provide a means to combine these and match them with the need where AM could be beneficial. These types of settings are similar to what Chesbrough (2003), Garud et al. (2013) and Van de Ven (2004) described (fast developing or emergent technologies).

The findings of this dissertation highlight different forms of interorganizational collaboration, starting from acknowledging a need, proceeding to contractual, then to more subtle influence, all the way to strong and symbiotic collaboration. In the systemic innovation context, interorganizational collaboration might even be seen as a precondition (Andersen & Drejer, 2008), particularly when the knowledge bases of organizations differ (Powell et al., 1996). This dissertation therefore illustrates the relevance of interorganizational collaboration (Arvanitis & Hollenstein, 2001; Larsson, 2020; Linton, 2002) through knowledge sharing (Frambach & Schillewaert, 2002; Talukder, 2014) and co-development (Arlbjørn et al. 2011; Chesbrough, 2003; Garud et al., 2013; Van de Ven, 2004), as an integral part of systemic innovation adoption.

To conclude, this dissertation contributes to technology innovation adoption knowledge by introducing two distinct elements of systemic manufacturing innovation adoption process. These are the complementary innovations that are required and the interorganizational collaboration that is used for both knowledge and capacity sharing and that is eventually part of the network that adopts parts of the "whole systemic manufacturing innovation," depending on their position and task orientation.

6 CONCLUSIONS

6.1 Theoretical contributions

Theoretical contributions are tightly knit together with what a theory is expected to convey. As the foundations of this study are geared toward interpretative constructivism and pragmatism, the theoretical contributions are to be found in the areas of interpretive sensemaking and contextual explanation (Welsch et al., 2011). Moreover, "interpretative theories allow for indeterminacy rather than seek causality and give priority to showing patterns and connections rather than linear reasoning… interpretive theory calls for the imaginative understanding of studied phenomenon" (Charmaz, 2006, pp. 125–126). Therefore, the contributions of this dissertation should not be used as a generalizable prescription to manage the adoption of AM, but rather as an understanding and some insights about the possible nuances that may take place during the adoption process. Also, the aggregated findings show the contextual elaboration of systemic manufacturing innovations for existing technology adoption process models.

This dissertation argues that the adoption of AM is interlinked with other innovations at the levels of the AM supply chain, process, and products—framing AM as a systemic innovation and its subsequent adoption. These complementary innovations take place simultaneously with the adoption of the new advanced manufacturing technology of AM. Therefore, successful AM adoption is connected to AM value chain adoption (or its creation and subsequent adoption). The new AM value chain is connected to the development of complementary innovations in supply chains (process) and successful AM product innovations. Additive manufacturing product innovation is again connected with value-driven design to develop an innovation in which AM adds value (Articles II and IV). Here, the value-driven design is the possibility of including sustainability as the value driver of the product outcomes of AM innovation (Article III). Furthermore, successful AM adoption requires overcoming the barriers to adoption, which requires identifying challenges to adoption (Articles I and II). Lastly, relevant to every aforementioned aspect is the interorganizational collaboration that needs to be taken into consideration when identifying challenges, establishing new value chains, and developing product innovations.

This dissertation contributes outside the AM literature to the technology adoption literature. This dissertation argues that systemic manufacturing innovation poses a specific case that adds to the theoretical knowledge about technology adoption (Clark, 1987; Davis, 1989; Mansfield, 1993; Milgrom & Roberts, 1990; Rogers, 1962, 2003). Additive manufacturing illustrates how a systemic manufacturing technology innovation requires complementary innovations (Chesbrough & Teece, 2002; Mulgan & Leadbeater, 2013; Takey & Carvalho, 2016) to become feasible to adopt. Therefore, the adoption of systemic innovation resembles a research project (Larsson, 2020; Romero et al., 2017; Tyre, 1991). In finer detail, however, it is not in only one single research project but in simultaneous or sequential research projects where the complementary innovations are developed. Perhaps due to the emergent nature of systemic and underlying innovation (AM), knowledge is scattered among organizations in an industrial network (Chesbrough 2003; Garud et al., 2013; Van de Ven 2004). For this reason, complementary innovations are developed through interorganizational collaboration (Andersen & Drejer, 2008; Powell et al., 1996), and consequently, the set of innovations has to be adopted by each organization in the generated novel value chain, which is also reflected by Maula et al. (2006).

This dissertation further contributes to the literature of AM adoption as a socio-technological phenomenon, providing a novel understanding about successful AM adoption through the lens of systemic manufacturing innovation adoption and thus answering the call for further studies of successful AM adoption cases by Ortt (2016; 2017), Steenhuis and Pretorius (2017), Rylands et al., (2016), and Ukobitz (2021). It has been shown that AM requires complementary innovation to be worth adopting. Product innovations are needed for AM adoption, and this dissertation's contributions to AM product innovation are related to studies of application recognition and AM added value (Chaudhuri et al., 2021; Fontana et al., 2019; Knofius et al., 2016; Lindemann et al., 2015; Rylands et al., 2016; Stentoft et al., 2021) by showing that identification of applications where AM adds value was positively related to successful adoption of the AM value chain.

The adoption of AM is connected to interorganizational collaboration, which is highlighted by findings about multiple companies and their differing challenges in adopting AM, which complements previous research in the sub-fields of AM adoption challenges that have not employed this wider interorganizational perspective (Chaudhuri et al., 2018; Cohen, 2014; Delic & Eyers, 2020; Fontana et al., 2019; Marak et al., 2019; Mellor et al., 2014; Oettmeier & Hofmann, 2017; Schniederjans, 2017; Schniederjans & Yalcin 2018; Sobota et al., 2021; Tsai & Yeh, 2019; Yeh & Chen, 2018). Furthermore, AM adoption and interorganizational collaboration are connected by the finding of emergent supply chain structures and relevant innovations at the AM supply chain level. This contribution complements previous relevant AM supply chain studies (Oettmeier & Hofmann, 2016; Rogers et al., 2016; Rylands et al., 2016; Thomas, 2016). These findings show that during the adoption of AM, interorganizational collaboration takes place in different places and in different phases as well as in different forms.

Since the adoption of AM as a systemic manufacturing innovation relies on complementary product innovations, there is the potential to include sustainability in new AM product innovations. Here, the contribution to the AM sustainability literature is made by connecting AM adoption and product innovations with sustainability considerations through value-adding design (Kritzinger et al., 2018; Maresch & Gartner, 2020; Ott et al., 2019). This dissertation further contributes by adding to and confirming the studies that have linked stakeholder influence and the attributes of AM product innovations to the end sustainability of AM (Beltagui et al., 2020; Ford & Despeisse, 2016; Gao et al., 2015; Maresch & Gartner, 2020) by showing evidence that external stakeholders are relevant in shaping the possibilities for desirable outcomes of AM innovations.

Figure 8 summarizes the key theoretical contributions of this dissertation. Figure 8 illustrates that the different key concepts presented in the introduction of this dissertation encompass the contributions of this dissertation and that they are connected and integrated with the key concepts.

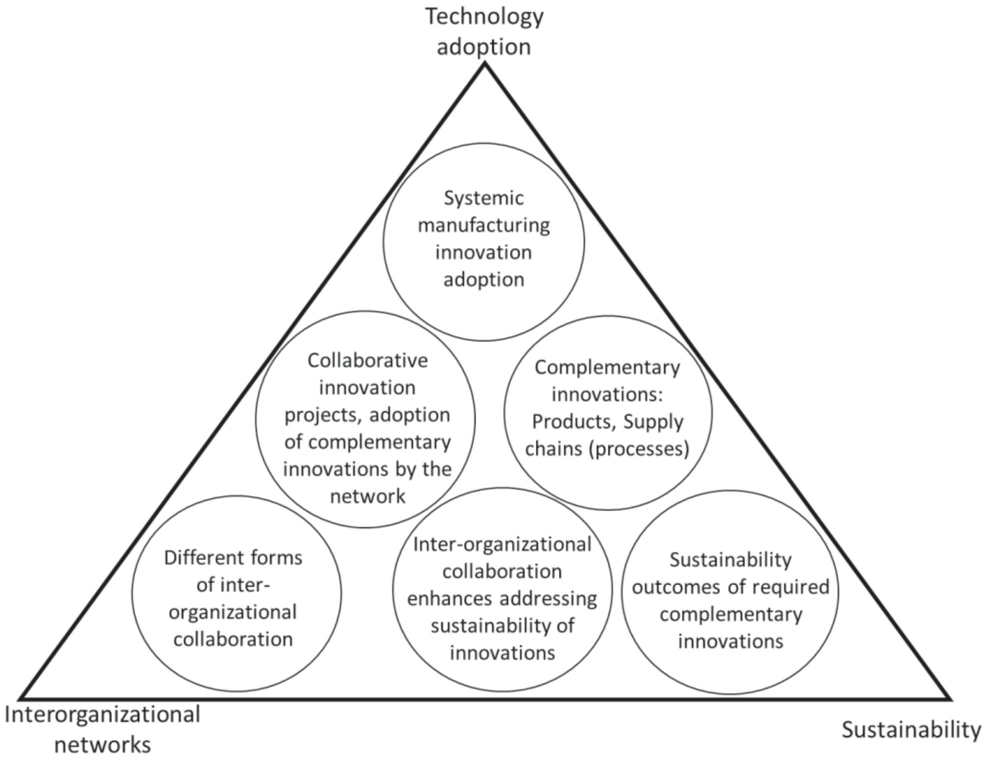

Figure 8. The contributions of this dissertation to the technology innovation context of additive manufacturing

6.2 Practical contributions

This dissertation makes practical contributions for organizations to better understand and manage the adoption of AM. First, a practical understanding of possibilities for SMEs in particular to position themselves in versatile supply chain alternatives and map their AM adoption challenges in comparison to others is provided. These insights also provide an understanding for larger companies or those actively supporting the adoption of AM in their value networks.

Engaging the supply chain more broadly in AM conversations will aid the various firms in justifying their investment decisions, negotiating their network positions, and gaining access to other enterprises as sources of complementary talents and knowledge. The findings inspire practitioners to look at AM adoption from a broader viewpoint through the lens of systemic innovation (i.e., including the supply chain, process, and product innovations) to support AM adoption. Neglecting the systemic nature of AM technology innovations, meaning that SMEs and major companies cannot grow their AM capabilities in isolation, on the other hand, can stifle or completely obstruct technology adoption.

Furthermore, because the implementation of AM may have an influence on the strategic location of manufacturing facilities and capability and skill needs at the industrial level, the findings can be used to design new training programs for SMEs or larger companies and can be consulted when funding institutions are reviewing the business plans of newly founded AM companies.

Managerial decisions may be informed by the contribution that demonstrates the influence of stakeholders (both primary and secondary) in the AM innovation process. This may prove to be especially important when organizations aim to improve sustainability and responsibility. The insights and developed framework in Article III offer organizations a way to start identifying key stakeholders who can support and enhance market access for socially desirable products and help gain other advantages during the innovation process.

The conclusions of this dissertation are potentially valuable to national and international innovation systems. As the manufacturing industry becomes digitalized in many nations, SMEs and larger companies alike will require expanded networks and support in order to embrace AM and encourage necessary changes in their business networks. The findings of this dissertation could act as a starting point for education providers to identify and prioritize AM-related learning content to educate manufacturing firm personnel.

The findings of this dissertation encourage organizations to educate themselves on the properties of AM, which will aid in recognizing applications where AM can add value. The findings illustrate that AM innovation projects that support AM adoption can be carried out in collaborative settings, where project participants' knowledge and abilities contribute to application recognition and value-driven design of AM goods, as well as the establishment of a new AM supply chain. Companies that understand the capabilities of unique AM technology and have the ability to find opportunities to add value to its application are viable collaboration partners for companies pursuing AM adoption.

6.3 Research evaluation

This dissertation is based on the philosophy of science orientations of interpretivism-constructivism and pragmatism and utilizes different methodological approaches, which all fall into the category of qualitative research. The research evaluation should mirror the philosophical and methodological choices of the researcher (Welch & Piekkari, 2017).

In qualitative research, especially when relying on interpretivism-constructivism philosophical orientations, it has been suggested that evaluation criteria that take the premises of this kind of qualitative research into account should be used (Eriksson & Kovalainen, 2008). One of the suggested evaluation criteria (Eriksson & Kovalainen, 2008) is the concept of the trustworthiness of the research (Lincoln & Guba, 1985), which covers four distinct aspects: credibility, transferability, dependability, and confirmability.

Credibility refers to how realistic the research findings and conclusions are, whether practitioners and readers find the study meaningful, and whether the findings make sense in general (Lincoln & Guba, 1985; Miles et al., 2014). In this dissertation, credibility was sought by diving deeply into the context of the study (Stake, 1995). I spent many months familiarizing myself with AM technology and the organizations interested in it. Throughout the research process, I participated in many industrial fairs, practical conferences, and scientific conferences to learn about the context and phenomenon I was studying. I also had several chances to present my findings to both practitioners and academics, and I received highly valuable feedback that enhanced the credibility of this dissertation and allowed me to be reflective. By reflexivity, I here mean an understanding of the researcher's own position, the practical and research community from which the knowledge has emerged, as well as an awareness of the situatedness of scientific knowledge (Hardy et al., 2001).

Transferability refers to whether the theoretical findings can be transferred to other contexts or settings (not generalized to a population) (Lincoln & Guba, 1985; Miles et al., 2014). However, as the researcher cannot be fully aware of other contexts, the transferability consideration is primarily the responsibility of the person seeking to transfer the results (Lincoln & Guba, 1985). Dependability refers to the quality of the research process in terms of rationality, consistency, traceability, and documentation (Lincoln & Guba, 1985; Miles et al., 2014). Lastly, confirmability implies that the researcher did not make up the findings and conclusions, but rather drew them from the facts in a verifiable and intelligible manner (Lincoln & Guba, 1985; Miles et al., 2014).

To enhance the three aforementioned aspects of transferability considerations, dependability, and confirmability, a researcher can make efforts to provide transparency in the study (Miles et al., 2014; Piekkari et al., 2010). With transparency in qualitative studies, the methodologies, data sources, and analysis methods should be truthfully explained (Bluhm et al., 2011). In addition to methodological transparency, the study should offer transparency in the findings through thick descriptions and researchers to describe how they discovered their insights (Bansal & Corley, 2011; Miles et al., 1994). Regarding this dissertation, an effort was made in each article to provide transparency regarding data collection and sources, methods, analysis, the contexts of the studies, and showing "raw" data alongside the interpretations to provide evidence for the conclusions.

As an integral part of research evaluation, the stance of "truth" should be discussed. Since this dissertation builds on an interpretative-constructive (and thus relativistic) orientation, that knowledge is considered relative to time and location, values subjective means, and posits that truth — or better truthfulness — is a matter of consensus among informed and sophisticated constructors (Patton, 2005). In addition, the second philosophy of science orientation guiding this thesis — pragmatism — assumes that the researcher can avoid metaphysical disputes about the nature of truth and reality in favor of "practical understandings" of tangible, real-world problems (Patton, 2005). Aiming to produce practically valuable findings arguably also supports the naturalistic evaluation criteria of Lincoln and Cuba (1985) and furthermore supports the perhaps lesser-known constructivist evaluation, highlighting the practical relevance and situated benefits for each stakeholder who considers the research useful (Guba & Lincoln, 1989). Simple but relevant explanations is one pragmatist way to achieve practical understanding (McDermid, 2006). In this dissertation the analytical tool to try to end up with simple explanations was visualizing the main findings into figures. However, I acknowledge that this takes expertise and could have continued even further to produce even simpler explanations.

Regardless of all the efforts to provide truthful findings for practice and theory, every study always has limitations, including this dissertation. Of course, the limitations are also dependent on the underlying philosophical orientation and aim of the research. The limitations might stem from methodologies, from data collection, and/or from the selection of data sources and data analysis.

Regarding limitations in methodology, Articles I, II, and III employed an explorative research design, which provided a broad exploration of the phenomenon but limited the depth of analysis. This kind of explorative research design could benefit from an even wider data sample to ensure that all the relevant findings surface—this, despite the fact that a certain degree of saturation was ensured before the data collection ended. Furthermore, Article III employed two workshops and one qualitative survey in between the workshops as a data collection method, which raises the possibility of bias among the informants. In workshops, the informants were discussing together, which makes them potentially prone for influence. However, as the aim was to explore the stakeholder groups and influences, this potential bias was considered acceptable, since it enabled informants to learn from each other and potentially realize important aspects that would not emerge otherwise. It should be noted that with another type of a research aim this kind of research design might not be appropriate.

Article IV, as a case study, has its own distinct limitations. Limitations regarding methodology include the choice of cases and whether they enabled new insights to surface. Regarding data collection, there are always limitations to qualitative data due to more or less restricted access to interview people from companies, as this is a cost for them. COVID-19 prevented live meetings, which may have caused limitations to interview length, content, and interviewees' willingness to share information. On the other hand it also enabled a more thorough treatment of secondary data covered in the interviews, due to video recordings. In addition, beliefs about the informants set up limitations regarding how the informants were perceived. If the informants are believed to be the best experts to tell the truth as they perceive it, then the limitation is whether the persons chosen for the interviews had the full and correct knowledge or whether there were enough interviewees for saturation of their views. If, again, it is believed that the informants are bounded in their rationality, the focus shifts to the researcher's abilities to dig out the meaning. Both of these limitations are naturally present in this dissertation.

Selection of data sources and collection of data included some limitations due to the chosen research context. From the technology perspective metallic and ceramic AM were studied, more specifically powder-based metallic (mainly tool steel and aluminum) AM technologies and slurry-based ceramic (metal oxides) AM technologies. Both metallic and ceramic AM have also many other technological solutions (for example filament-based ones) and studies focusing on those could provide different findings. The industrial fields where AM was adopted and consequently studied also causes limitations to validity. In this dissertation, machine building and process technology industries within Finnish organizations and biomedical and automotive industries within European organizations were the focal fields. These limitations should therefore be taken into account when transferring the findings to other contexts.

There are also limitations regarding the researcher collecting the data and analyzing it. I argue that there is always a limitation in the researcher with regard to knowing the research topic so that even the finest nuances can be discovered in interview situations. Or, again, there is always another analytical framework available that can be used in the analysis and that could lead to other findings, as well as the question of whether the researcher's cognition functioned clearly at the time of conducting analysis. Here, the aforementioned measures to increase the credibility of the study also support overcoming the limitations of the researcher. Reflecting on the results with a coauthor, presenting intermediate results and collecting feedback in conferences and research project workshops, and publishing results in peer-reviewed journals all contribute to ensuring that no obvious error of thought has occurred during the analysis.

Finally, the limitations of an article-based cumulative dissertation deserve some discussion. Besides a sequentially conducted study built around the emerging technology of AM, this dissertation is also an academic thesis to prove that the requirements for a doctoral degree are met. In this dissertation, a series of empirical exploratory studies, each with somewhat different conditions, contributed to the article compilation. The separate studies occurred in separate projects, each with its own funding and partners. The projects required me to participate in additional research activities parallel to the research included in the dissertation. As a result, the conceptual and empirical connections between the articles in this dissertation are limited through the projects that enabled them. While Articles I and II represent the same context, they differ clearly from the contexts of Articles III and IV, which necessitated the article-specific consideration of research validity. At the same time this research design allowed the research ideas to emerge as they appeared in different real-life AM adoption settings. Despite the limitations caused by the different project settings, the exploratory approach enabled the practical topicality of each separate article.

Binding the articles together into a coherent compilation required extra effort to assess how they would answer the research questions of the dissertation as a whole. This dissertation purposely pursued meaningful contributions overarching the four different articles, instead of writing a referential introduction for the articles only. I had to put effort and find a multi-perspective analysis level to establish commonality across the separate studies and results based on the analysis of different data and contexts. In hindsight, if I were to start this research again, I would consider the research design more thoroughly in advance. I would plan the research and select the studied AM innovation contexts so that the sequential articles would fit together more seamlessly, if the research funding would allow it.

6.4 Future research

Future research opportunities lie in multiple directions. As the main purpose of this dissertation was to use qualitative methods to create a new understanding as a theoretical contribution, a future research opportunity would be to design a quantitative study to measure the statistics of the identified issues. Quantitative research approaches could be utilized in a quest to find generalizations, but in this dynamic phenomenon of AM adoption in industries, the rationale for generalizations must be carefully weighed (for whatever pragmatic reason there would be to generated snapshot-like generalizations).

The contexts of this dissertation provide another future research avenue, as in different contexts, different theoretical and practical contributions could be made. Addictive manufacturing adoption could be studied in detail in other settings, such as different industries and with different network formations. For example, cases where AM machines are invested in and purchased due to AM adoption would be an interesting future research avenue, particularly if interorganizational collaboration is as apparent in these situations. The differences of AM technologies could be further studied. In this dissertation the focus was on powder-based metallic and slurry-based ceramics, but there are many other technology solution and material combinations. For example, the adoption of extrusion-based polymer AM in contrast to powder-based metallic AM would provide an interesting future research direction, not to mention extrusion-based metallic AM in comparison to powder-based one.

Furthermore, the different contexts in terms of different application areas in which completely new products (radical AM product innovation) are developed during AM adoption are possible future avenues to complement the findings of this study, where the AM applications were developed from existing solutions. The relationship between specific AM technology and specific material choices (i.e., technological solutions coupled with industry and innovations) should be studied in more detail. In this study, the available AM technologies and raw materials were somewhat limited due to the early phase of AM diffusion. However, as time advances, more AM technologies and materials will become available, and these technological properties are relevant for application recognition and product and process innovation and therefore to AM adoption in networks and diffusion on a large scale.

In this dissertation, the contributions were made to the generic technology adoption literature in terms of expanding the theory with the systemic innovation adoption view. The use of AM in a specific industry, in specific supply chains, might offer interesting future research directions in terms of contributing to the theory of AM supply chain management. For example, it could be beneficial to investigate transactional versus collaborative relationships in AM supply chains and their related conditions, or producer-driven supply chains versus buyer-driven supply chains in the context of AM adoption.

Regarding sustainability, the literature review revealed that previous studies have two distinct ways of conceptualizing sustainability. Either the manufacturing process or AM technology itself in contrast to traditional manufacturing (this means, for example, the manufacturing of an electric car, starting from mining the battery materials and ending with a car to be sold). Or then the end result of what is manufactured can also be evaluated in terms of sustainability (as an example, this refers to driving an electric car). Because this dissertation focused on the AM innovations required for AM adoption, the latter was studied. However, in the future, both aspects should be studied together, and this will likely require more AM adopters and promising applications to make the study feasible. This future research avenue is linked to the idea of coupling technical solutions with new applications.

Future research on sustainability and responsibility could even be taken in a far more ambitious direction. Innovations that originate from ideas for solving an ecological or societal problem as the main driver and managing them so that it is possible to allow widespread diffusion within the economic system are certainly needed, and the first possible cases should be studied. This is because it is not self-evident that beneficial innovations will be accepted and adopted by users (organizations or individuals); thus, there is research needed to understand and support the adoption of socially and sustainability desirable innovations at an organizational level and diffusion at a societal or industrial level. Furthermore, there is an imminent need to understand how such innovations have been initiated and developed and how to communicate the real results of their ecological impact. This knowledge needs to be diffused to the next generation of business and science, technology, engineering and management professionals to create a sustainability movement apart from ecologically and socially harmful businesses and to foster economic wealth at the same time. A research direction based on innovations that solve an ecological or societal problem would take the research to the next level, as the literature review and the findings of this dissertation revealed that currently, sustainability in relation to innovations involves making informed decisions so that the sustainability outcomes are "only" less harmful than proprietary solutions.

Finally, this dissertation offers the novel contribution that the adoption of AM as both a systemic and an advanced manufacturing technology challenges traditional technology adoption theories. The systemic nature of AM innovation therefore offers even wider future research avenues for studying how the systemic nature is present in the technology development phase that takes place before the adoption phase in organizations. I propose the following research question for future research: "How do systemic innovations emerge and evolve over time in and between AM technologies?" This has the potential to contribute to the evolution and diffusion of technology by expanding the view to acknowledge the systemic evolution and diffusion of AM innovations.

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Adopting additive manufacturing in SMEs: Exploring the challenges and solutions

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Adopting additive manufacturing in SMEs: Exploring the challenges and solutions

Miia Martinsuo and Toni Luomaranta

Laboratory of Industrial and Information Management,

Tampere University of Technology, Tampere, Finland

Abstract

Purpose: Adopting additive manufacturing (AM) can be challenging, especially in small and medium-sized enterprises (SMEs) and as part of the supply chains of larger firms. The purpose of this study is to explore SMEs' perspectives on the adoption of additive manufacturing in their specific supply chain positions. The paper develops new knowledge on the challenges SMEs face across the supply chain and the actions they need to promote the adoption of AM.

Design/methodology/approach: An exploratory interview-based research design is used. Seventeen interviews were conducted and analyzed in four types of SMEs in their specific positions in AM supply chains. The challenges of adopting AM were mapped, and actions to promote AM adoption were identified.

Findings: SMEs in different supply chain positions experience different challenges when adopting AM. Strategic and operative actions are suggested as key solutions to overcome the challenges. The benefits of AM on a large scale will be achieved only if the broader supply chain adopts AM technology and experiences its benefits.

Research limitations/implications: The research is limited by its single-country context, its focus on SMEs, and the selection of early-phase AM adopter firms. The findings imply a need to understand AM adoption as a shared concern and systemic innovation in the supply chain, instead of just a firm-specific implementation task.

Practical implications: The findings offer a framework for categorizing AM adoption challenges and propose ways to overcome the challenges of adoption.

Originality/value: The study reveals that AM adoption is not only a technology issue, but an issue of strategic, organizational and operational challenges across the supply chain. It shows that when adopting AM, SMEs face particular challenges and require specific solutions according to their supply chain position.

Keywords: Additive manufacturing; Advanced manufacturing technology; Small and medium-sized enterprises (SMEs)

1. Introduction

Industrial competitiveness is no longer a single firm's concern, and requires multiple firms in the supply chain to interact—including small and medium-sized enterprises (SMEs). Additive manufacturing (AM) represents a topical innovation in manufacturing technologies, and it may significantly change value chains and business logics in manufacturing industries (Steenhuis and Pretorius, 2017). In contrast to more traditional digital manufacturing technologies that remove materials from the item being manufactured, AM technologies process materials by joining and adding to them, usually layer-by-layer (ASTM, 2012), to make an object from a digital model. AM technologies can be considered advanced manufacturing technologies (Arvanitis and Hollenstein, 2001), and they are also a means of rapid prototyping and manufacturing (Hopkinson et al., 2006; Mellor et al., 2014), particularly if intended for components or products for actual end use. The implementation of AM technologies is not currently widespread, and it may be slow. This paper explores SMEs' AM adoption, challenges, and requirements.

AM has attracted increasing attention in both technology-based firms and management research, largely because AM technology usage can have far-reaching implications for businesses (Oettmeier and Hofmann, 2016; Steenhuis and Pretorius, 2017). Companies are drawn to experiment with AM for a variety of reasons, including efficiency, flexibility, and innovation potential (Holmström et al., 2010; Weller et al., 2015). Despite growing interest in AM, its potential business applications are just now emerging (Oettmeier and Hofmann, 2017), and its broader adoption requires solving not only technology issues, but various issues in new kinds of supply chains. AM technologies and applications are evolving rapidly and continuously, thereby necessitating research to discover means for overcoming the barriers to technology transfer (Oettmeier and Hofmann, 2017; Flores Ituarte et al., 2016b) and to identify how and where to introduce AM (Niaki and Nonino, 2017; Ruffo et al., 2007).

This study focuses on the need to understand the role of SMEs in adopting AM to achieve supply chain-level changes in AM-related new businesses. SMEs may appear in many different positions in manufacturing supply chains, and they are presumably facing challenges in their attempts to adopt AM.

SMEs differ from large firms in many ways. Generally SMEs are thought to have a fewer available resources (Tovstiga and Birchall, 2008), less specific divisions of labor (Vossen, 1998), and less bureaucracy (Rothwell, 1989) than large firms, and these characteristics have implications for their development and innovation activities. More innovation-specific differences have also been pointed out, including SMEs' risk aversion in innovation activities (Lasagni, 2012), lack of systematic development procedures (Tovstiga and Birchall, 2008), and greater capacity to absorb new knowledge and technologies (Vossen, 1998). Understanding of the particular features of SMEs is pertinent to understanding how their AM adoption can be supported.

Most recent studies have shown that AM is used in niche applications alongside traditional large-scale manufacturing technologies (Ortt, 2016; Rylands et al., 2016). SMEs' role in the future of AM may be even larger than that of bigger global players (Rogers et al., 2016) because SMEs adopting AM may be capable of transforming themselves into direct digital supercenters (Sasson and Johnson, 2016). However, the adoption of AM in SMEs is currently poorly understood, as the majority of the literature focuses on large firms, or a mix of large firms and SMEs, and overlooks the supply chain positions of the firms. With limited resources and experience with technological innovation, SMEs require more effort to integrate AM into their existing systems (Oettmeier and Hofmann, 2016). There is a need to understand SMEs' perspectives on AM technology adoption in order to strengthen their position in modern manufacturing value chains.

This paper explores SMEs' perspectives on the adoption of AM in their supply chains. The goal is to identify the different types of challenges and requirements for adopting AM across different supply chain positions, and develop new knowledge on the practices that are needed to promote AM adoption. The focus is on the following research questions:

1. How do SMEs in different supply chain positions differ in their challenges in adopting AM?
2. How can SMEs overcome the challenges?

This paper adds to AM technology adoption literature that calls for more research on different industrial setups (e.g., Mellor et al., 2014; Oettmeier and Hofmann, 2017) by revealing the realities of SMEs. The research contributes to the discussion on AM adoption by identifying the key challenges experienced by different types of SMEs, and proposing means to overcome them. The focus is on different SMEs in company networks where AM is experienced as relevant (i.e., adoption of AM is topical), but not yet part of the mainstream, whereas the major application industries already deeply engaged in AM are excluded. We have purposefully excluded large firms as previous research has already covered their experiences.

We first review previous research on the forces driving AM adoption, experiences of adopting AM, and the barriers that have been identified so far. We then introduce the exploratory research design, covering interviews with managers in 17 SMEs considering adopting AM in their businesses. We map the challenges that the interviewees have experienced in adopting AM, and propose solutions. Finally, we draw conclusions about AM adoption in SMEs, discuss actions to promote broader AM adoption in the supply chains of SMEs, and suggest pathways for further research.

2. Literature review

2.1 Additive manufacturing: Drivers and benefits

Additive manufacturing may drive radical changes in how manufacturing industries and societies operate (Ortt, 2016). AM is not a single technology, but a set of several—all at different stages of development—enabling the use of various materials and different levels of output quality (Ford et al., 2016). Different AM technologies exist; they all are relevant manufacturing innovations, and all require that firms exert effort for their adoption to be useful for businesses. Although AM technology has existed for almost three decades, academic research on it from the perspective of business and supply chains has only begun recently and is still in an emerging, exploratory phase (Ortt, 2016).

Previous research has emphasized various benefits of using AM technologies, including design freedom, efficiency and speed, customization of products, enabling of small batches, flexibility, adaptability, simplification of supply chains, and reduction of waste (Berman, 2012; Holmström et al., 2010; Flores Ituarte et al., 2016b; Niaki and Nonino, 2017; Weller et al., 2015). Sometimes, AM is compared with traditional advanced manufacturing technologies and the benefits of achieving flexibility and complexity "for free" are emphasized (Weller et al., 2015). The main benefits for SMEs are suggested to be the high level of customization, flexibility, possibilities in logistics management, and potential for production cost savings (Mellor et al., 2014).

By adopting AM technologies, companies may reap a variety of strategic rewards. For example, small- and medium-batch production could be transferred back from low-wage to high-wage countries, since AM may reduce the need for manual labor (Berman, 2012). The economic benefits have been emphasized, potentially because of the inventory turnover decrease stemming from on-demand manufacturing, flexible use of manufacturing equipment, and energy savings (Niaki and Nonino, 2017). AM can provide a competitive advantage, especially if the market is uncertain and demands a great variety of products and adaptability to varying customer needs (Weller et al., 2015), along with a shorter time to market (Niaki and Nonino, 2017). Some AM applications have the potential to enhance productivity when manufacturing on a large scale (Flores Ituarte et al., 2016b). AM may additionally offer novel innovation possibilities both in products and processes (Niaki and Nonino, 2017), thereby helping to reach new customers (Mellor et al., 2014) and creating products that were not possible with other manufacturing technologies (Mellor et al., 2014; Niaki and Nonino, 2017).

For customers, the flexibility and adaptability AM technologies enable can offer useful outcomes. Customers ordering AM components may benefit from the higher service levels, as production may be decentralized and located closer to customers (Khajavi et al., 2014). AM can potentially integrate customers better into the value creation process and mitigate the problems in economies of scale and product variety (Oettmeier and Hofmann, 2016; Rylands et al., 2016). Customer needs can be met better by creating products that fulfill their requirements, as AM offers almost unlimited freedom of design (Diegel et al., 2010), making real mass-customization of products possible (Deradjat and Minshall, 2017; Niaki and Nonino, 2017).

2.2 Adopting AM in different firms

At the industry level, the pace of AM technology diffusion depends on how different firms bring the technologies into use and develop commercialized solutions based on them. Some previous research covers the overall process through which AM is adopted in firms (Rylands et al., 2016; Oettmeier and Hofmann, 2017), in line with earlier research on technology adoption and diffusion (Davis et al., 1989; Rogers, 1962, 2003). An initial approach would require the piloting of low-volume production using AM as a new manufacturing opportunity (Flores Ituarte et al., 2016b).

To convert the use of AM technologies into profitable business, companies need to manage complex innovation and socio-technical processes. Paying attention to technical and economic issues only is insufficient when adopting AM (Farooq and O'Brien, 2012); it is likely that strategic production plan changes are needed (Oettmeier and Hofmann, 2016). Manufacturing firms should consider the potential effects of AM on their supply chains, processes, and management when deciding whether to adopt AM technologies in their industrial parts production (Oettmeier and Hofmann, 2016).

Companies have two different options when engaging in the field of AM: they can source ready-made AM parts (contract manufacturing or service), or invest in machinery and source required materials (Oettmeier and Hofmann, 2016). In both cases, there are a variety of factors that may influence a firm's intent to adopt AM technology, including: technology-related, firm-related, market structure-related, and supply chain-related factors (Oettmeier and Hofmann (2017). Mellor et al. (2014) formed a conceptual framework of the socio-technical factors relevant in AM implementation, including strategic, technological, organizational, operational, supply chain-related, and external factors. They found that both external forces and internal strategies are driving AM adoption in the context of a rapid prototyping company converting to rapid manufacturing, and proposed that the framework be used in future studies in other contexts and scenarios.

The size of an organization has been identified as critical to understanding the process of adopting new manufacturing technologies. A number of scholars have suggested that small businesses cannot be considered as scaled-down larger businesses, and the theories proven using large enterprises may not apply to them (Federici, 2009; Thong et al., 1996). Studies covering SMEs' adoption of traditional advanced manufacturing technologies show that SMEs have a short planning horizon: they tend to use reactive mechanisms to keep customers satisfied by fulfilling existing orders, thereby overlooking long-term and strategic planning (Fulton and Hon, 2010). SMEs are often unaware of the benefits of new manufacturing technologies (Fulton and Hon, 2010), and they may lack management commitment as well as financial and human resources for technology investments (Thomas et al., 2008). Due to their limited bargaining power, it is possible that SMEs do not easily get support from manufacturing technology suppliers, and they may lack long-term relationships with major customers (Mishra, 2016). Furthermore, even within the sector of manufacturing SMEs, company profiles are very heterogeneous and they can differ in their technology-intensity, innovativeness, and ambitions for growth (Thomas et al., 2008). Since AM utilizes digital models, it is not just manufacturing firms, but also industrial design SMEs that need to adopt AM. Previous studies have recognized inadequate inter-organizational information systems and the strong dependency of SMEs on the supply chain partners as factors possibly hindering the adoption of digital supply chain innovations (Archer et al., 2008). Also the lack of standards can be a challenge in adopting digital model-driven engineering (Peltola et al., 2011). To conclude, an SME's approach to AM adoption is likely to be different from that of a large multinational company (Mellor et al., 2014). Previous research has to some extent covered SMEs' views on AM adoption, as shown in Table 1.

Table 1. Overview of empirical studies on AM adoption, partly covering the views of SMEs.

Source	Method and context	Findings	Gap justifying this study
Mellor et al., 2014	Single case study. European SME industrial goods manufacturer, both plastic and metal parts in-house. Parts for different industrial sectors. AM application: end-use components.	Conceptual framework of important factors in AM implementation created and tested.	Single case; framework should be tested further in different industry scenarios.
Flores Ituarte et al., 2016b	Single case study. Global consumer electronics manufacturer, focus on plastic parts, in-house AM prototyping, outsourced AM manufacturing. AM application: prototypes and end-use components.	AM technology has not yet penetrated the current supply chain structure, considerable barriers exist in transferring AM to engineering applications.	Single case study in a large firm; emphasizes the importance of supply chains regarding AM adoption, encourages further research from technical, organizational, and managerial standpoints in different industry scenarios.
Oettmeier and Hofmann, 2016	Two-case study. European large and medium hearing aid system manufacturers. Plastic AM in-house. AM application: end-use products.	AM affects internal processes, management activities, and supply chain processes.	Two cases, of which one is medium-sized; further research needed on engineer-to-order environment, procurement of ready-made AM parts, interaction between purchasing firm and contract manufacturer, and different industry scenarios.
Rylands et al., 2016	Two-case study. European SME manufacturers: industrial and commercial. AM application: Production process (tooling).	AM adoption process and business impact model. Implementation of AM causes a shift in value proposition, AM complements traditional manufacturing.	Two cases; model requires further evidence and additional research on how AM adapts to suit new industries.
Deradjat and Minshall, 2017	Multiple case study of 6 firms. Large and SME dental and medical implant manufacturers. AM application: metal end-use implants.	Implementation of AM faces different considerations depending on the stage of implementation and maturity of technologies, as well as company size.	Future research to study other applications for AM in mass customization.
Niaki and Nonino, 2017	Exploratory study with 16 firms. Large and SME manufacturing companies in Italy and US. Various industries. AM application: various technologies and various applications not specified.	Implementation of AM has boosted productivity of metal AM products.	Further research should also study companies that have not adopted AM.

Source	Method and context	Findings	Gap justifying this study
Oettmeier and Hofmann, 2017	Questionnaire survey (n=195). Large, medium, and small companies; adopters and non-adopters; various industries. AM application: wide range of materials and applications.	Supply chain-related factors have a strong influence on AM adoption.	Future research should provide insight into the drivers of AM adoption; different supply chain positions considering AM should be investigated.

A majority of the studies include both large firms and SMEs (Oettmeier and Hofmann, 2016, 2017; Flores Ituarte et al., 2016b; Niaki and Nonino, 2017; Deradjat and Minshall, 2017) and emphasize the possibilities and adoption requirements of AM technologies. Only a few studies have focused on SMEs specifically and tend to be small-scale case studies (Mellor et al., 2014; Rylands et al., 2016), offering a very limited perspective on the specific nature of adopting AM. Previous research has studied AM adoption only from the viewpoint of a single supply chain position and use case companies from the aerospace, automotive, dental, medical, marine, defense, and pharmaceutical industries (e.g., Oettmeier and Hofmann, 2016, 2017; Mellor et al., 2014), where leveraging of AM provides strategic benefits, or only concern plastics (Flores Ituarte et al., 2016b). The study of Rylands et al. (2016) is an exception where case companies are adopting AM to enhance their production system in a very different industry set-up. Further research is needed to cover multiple supply chain positions in AM networks and outside of the advanced AM-adopter industries.

2.3 Challenges in adopting AM and overcoming them

AM technology is not a response or solution to every manufacturing concern, and it may suffer from trade-offs compared to traditional manufacturing, e.g., in terms of available materials, costs, processing speed, energy consumption, and industry-level standards (Mellor et al., 2014). The main barriers for SMEs are suggested to be the cost of AM machines and lack of highly-skilled personnel (Mellor et al., 2014; Niaki and Nonino, 2017). These can generate barriers for firms adopting AM if they do not simultaneously find clear strategic advantages. Various barriers have been mapped in some conceptual studies (e.g., Berman, 2012; Ruffo et al., 2007). Challenges in and barriers to AM adoption discovered in previous empirical studies are quite varied, and Table 2 summarizes them, using Mellor et al.'s (2014) thematic categorization into technology-related, strategic, supply chain-related, operational, organizational, and external AM implementation factors.

Table 2. Previously identified challenges to AM adoption.

Type of challenge:	**Technology-related**		**Strategic**		**Supply chain-related**		**Operational**		**Organi-zational**		**Extern al**
Empirical studies	Technology	Material	Strategic	Investment/ Operational costs	Supply chain	Customer	Design	Operation /Process	Skills /Learning	Management	Market
Gausemeier et al., 2013	x	x					x				
Mellor et al., 2014	x			x	x	x	x		x		x
Flores Ituarte et al., 2016b			x		x					x	
Oettmeier and Hofmann, 2016			x		x				x		
Deradjat and Minshall, 2017	x	x	x	x	x			x	x		
Niaki and Nonino, 2017	x	x		x							
Murmura and Bravi, 2017	x			x					x		

The review of previous empirical research shows that the majority of the research concerning challenges to AM adoption have been carried out either solely in large firms (Flores Ituarte et al., 2016b), or in a mixed setting of different–sized firms without explicitly uncovering the viewpoint of SMEs (Gausemeier and Echterhoff, 2013; Niaki and Nonino, 2017; Deradjat and Minshall, 2017). Evidence on SMEs shows that in contrast to large firms that can utilize their expertise internally and have the capital to invest in several AM machines in-house to solve operational challenges, SMEs suffer from a lack of capital and expertise, meaning they have to rely on collaboration with external partners (Deradjat and Minshall, 2017). This tight dependence on external supply network partners creates an entirely new dimension for AM adoption among SMEs, and calls for new knowledge and research.

Overcoming the challenges of AM adoption may take many forms, including investments into technological advances (Weller et al., 2015), innovations in design (Mellor et al., 2014), strategic value chain changes, manufacturing relocation (Flores Ituarte et al., 2016b), and developing specialized know-how (Oettmeier and Hofmann, 2016). Where certain studies offer partial solutions to overcoming specific barriers, there is a need to holistically develop further knowledge on AM adoption challenges and their solutions among different types of SMEs.

3. Research methods

3.1 Research design and selection of companies

This research focuses on the adoption of metallic AM within SMEs in prospective new AM application industries, namely the machine manufacturing and process industries. As a contrast to previous studies that mostly examined technology-centric larger firms, combined large firms and SMEs, or only took a single-company perspective, this research is exploratory, and attempts to address a larger variety of SMEs in different kinds of supply chain positions in machine manufacturing and process industries where the use of subcontractors is common.

SMEs were sought from a delimited geographical region, and they were expected to be somewhat related to the manufacturing industry in the region. We focused on SMEs in different positions in AM supply chains, including design, subcontracting, original equipment manufacturing, and service provision, with the expectation of gathering about 20 interviewees to enable comparison across supply chain positions. Altogether, 17 companies participated. Table 3 summarizes the target companies and provides some context. We use letter codes to denote the companies, to maintain their anonymity and confidentiality. With this sampling approach, a good variety of different types and sizes of SMEs was achieved. All of the firms stated their willingness to be active innovators in order to maintain their competitiveness in their supply chain. The firms can be into divided into four clusters: medium-sized original equipment manufacturers (OEMs), small or medium subcontractors, small subcontractors providing AM services and an AM machine supplier, and firms providing engineering and industrial design.

Table 3. Background information on companies and interviewees included in the study.

Type of company	Company code	Nr. of emp-loyees (appr.)	Inter-viewees (nr)	Respondents' positions	Experience in AM	Inter-view dura-tion (mins)
Medium-sized OEMs (Cluster 1)	Company A	200	1	Production development manager	Rapid prototyping	65
	Company H	50	1	VP of Technology	Rapid prototyping	83
	Company I	200	2	CEO; CFO	Rapid prototyping & manufacturing	63
	Company K	150	1	R&D manager	Rapid prototyping & information	58
	Company M	60	2	VP of R&D; R&D engineer	Rapid prototyping & information	69
Small or medium subcontractor (Cluster 2)	Company B	50	1	Managing director	No experience	71
	Company E	15	2	CEO; Chief design engineer	Post-process	72
	Company F	160	1	Production R&D engineer	Rapid prototyping & tooling	77
	Company J	20	1	Managing director	No experience	51
Small subcontractor / AM service provider using AM	Company N	5	1	CEO	AM machine	75
	Company Q	5	1	Sales & marketing manager	AM machine	43
AM machine supplier (Cluster 3)	Company O	20	1	Business development director	AM machine supplier	98
Engineering and industrial design (Cluster 4)	Company C	1	1	Entrepreneur	Rapid prototyping & manufacturing	40
	Company D	5	1	CFO	Rapid prototyping & information	69
	Company G	280	2	VP; Chief design engineer	Testing rapid manufacturing	81
	Company L	70	1	VP	Rapid prototyping	80
	Company P	1	1	Entrepreneur	Rapid prototyping, manufacturing & tooling	70

3.2 Data collection

Interviews with SME managers are used as the primary data source, along with two researcher workshops and four workshops with SME managers as the secondary data to validate the findings from the interviews. A total of 21 people were interviewed using a thematic outline to identify the challenges associated with AM adoption and their possible solutions. Table 3 shows that the interviewees are top managers in SMEs, as they were considered key decision makers regarding the adoption of new technology.

The interview outline was developed jointly in the research team based on key issues identified in the literature, and ideas were proposed during two company workshops. The interview outline was initially tested with the first interviewees and subsequently modified for further use. The interviews covered the following themes: the background and position of the respondent; the company's experience and plans for adopting AM; identified challenges in implementing AM; possible industry-specific needs for AM; opportunities to add value for the business and its customers by using AM; and production and supply chain changes required by AM. For Cluster 3 (firms operating AM machines and an AM machine provider), an additional question regarding their customers' challenges in adopting AM was added. All the interviews were recorded and transcribed, and brief notes were taken.

Secondary data were collected in the workshops with industry participants. Two researcher workshops were used to validate the interview frame, discuss the findings, and identify potential analytical frames. Two of the company workshops were used to establish an initial understanding of the AM field, and two were used to report and test some of the interview findings. Workshops were documented through handwritten notes.

3.3 Data analysis

In the first phase of reading the interview transcripts, the data were explored to note locations where possible challenges and requirements regarding AM adoption were discussed, and examples of their potential solutions were mentioned. In the second phase, the focus was on the challenges. Common themes and patterns were identified, particularly concerning the challenges of AM adoption, using Mellor et al.'s (2014) thematic framework as a starting point for coding the interviewees' experiences. Such frameworks point out various technology-related, strategic, supply chain-related, operational, organizational, and external factors in AM adoption, and these rough themes were used as the starting point for coding. All the different challenges to adopting AM in SMEs were identified and grouped into these themes. To identify potential differences across company types, we checked how frequently each topic appeared in the interviews per company cluster, and built a cross-tabulation covering all the challenges and their comparison across company clusters.

In the third phase, the requirements and actions for promoting AM adoption were coded. The initial reading of the data suggested that most of the requirements intersected with multiple challenge-related themes. Therefore, an inductive approach was chosen to let the solution categories arise from the data. The five main requirements in promoting AM adoption deal with AM technology, knowledge, strategic decisions, digitalization, and cooperation. Finally, the challenges and requirements of AM adoption were processed in two workshops to identify actions to help the SMEs overcome the challenges. Six actions (three strategic and three operational) are proposed, structured according to the AM implementation factors (Mellor et al., 2014). In reporting the findings, we use quotations from the interviews, and calculated frequencies and cross-tabulations of key issues.

4. Results

4.1 SMEs' experiences of challenges in AM adoption

A total of 33 different challenges were identified among SMEs in AM adoption, and we summarize the technology-related, strategic, supply chain-related, operational, organizational, and external challenges here. *Technology-related challenges* appeared as the third most often mentioned among the companies in this study. Technological challenges were particularly experienced in OEMs and subcontractor firms that have a manufacturing position in the value chain. They included material and quality challenges, long production time, size limitations, technological immaturity, and missing cost calculation models. For example: "*When thinking whether it is possible to make a certain type of component by AM in a demanding operating environment, then firstly, the dimensions are critical, the piece is too big to fit on the AM platform and then the material requirements are hard, compared to what is available for AM, and then the price is of course going to be the limiting factor*". (Cluster 4, Company D) The technological challenges appeared rather inconsistent among the different types of firms; even if service providers and industrial designers also experienced some technical challenges, they were somewhat different from each other and those of the manufacturing firms.

Strategic challenges were discussed among the interviewees the least often, and they were particularly apparent among the manufacturing firms. Interviewees from OEMs and subcontractor firms stated that they lack a company-wide strategy for AM, and an interviewee in a service provider firm said that it seems to be the challenge amongst their customers. Adopting AM is, therefore, not yet strategic or systematic and it may rely only on one person's interest in the technology. Interviewees in SME subcontractor firms in particular expressed that they are afraid to invest in AM machines since it is so expensive, and payback is not guaranteed.

Supply chain-related challenges were experienced among the interviewees not only in terms of the supply chain itself, but the digital solutions through which data are transmitted between supply chain actors. Uncertainty of the emerging supply chain structure was considered a challenge to AM adoption by three-quarters of the subcontractors. Their uncertainty regarding their own position in the emerging supply chain lessens their enthusiasm for adopting AM, at least in terms of investing in machinery. Interviewees in subcontractor and industrial design firms emphasized digitalization-related challenges in the supply chain. Subcontractor firm interviewees said that paper blueprints remain the industry standard, and if a customer sends a 3D model it is done with a poor transfer standard, as the 3D models are not yet supported. If a better standard, for example STEP 242, were more widely used, subcontractors themselves would decide which manufacturing method was the most suitable. An interviewee explained this challenge as follows:

"Not a single well-supported 3D model has come out, yet. I would say that it is the inexperience of designers that it only comes as a STEP-203 model and with information that does something like this. Then we need to go through a lot of trouble to find out what the designer really wants this component to do. For example, there is a free hole – should we make threads there? The 3D model does not explain such details if there is no data entered into the 3D model. Consequently, it is necessary to always have a 2D drawing that explains the details and tolerances." (Cluster 2, Company E).

Interviewees, especially in the industrial design firms, also pointed out that design software is expensive and simulation programs for AM are underdeveloped, which creates challenges to even start to design components to be manufactured using AM.

Operational challenges were expressed concerning design and development as the second most typical challenge, and the challenges stated appeared fairly evenly across the company clusters. Designing for AM and its challenges was discussed in many firms. The legacy of existing product designs and their unsuitability for AM were also discussed. In the relatively early stages of AM, products have to be specifically designed for AM and most likely to a specific machine. Interviewees in the OEMs emphasized the need to identify the right components for AM manufacturing, which is not easy. These challenges can be partly explained by the habit of sticking to old practices and the mindset of "if it ain't broke, don't fix it." The cost of AM components, together with the lack of good cost calculation models, creates another challenge, when the benefits may be realized only during the lifecycle of the component. An interviewee from a service provider firm described the challenging link between design and production as follows:

"Parts that come to be printed are still clearly designed for other manufacturing methods, even though the parts are topologically optimized, and for some reason, the customer may not necessarily even want to change it. Then, the challenge is that when you may not understand the manufacturing method properly, it is very difficult to start discussing optimization and such if the customer has no idea of this manufacturing method. There are still a lot of different weird preconceptions about the AM, or it is compared directly to machining, for example. It may be that

company bureaucracy prevents or makes redesigning a particular product for this manufacturing method too slow." (Cluster 3, Company Q).

Organizational challenges were expressed in terms of lack of knowledge and readiness, and satisfaction with the status quo. Organizational challenges appeared as the most frequently expressed challenge. Interviewees in OEMs, subcontractor, and industrial design firms stated that the lack of knowledge about the technology is a clear barrier to adopting AM technology, even if some experiments have been carried out. AM components (costs, manufacturing time, surface quality, etc.) are directly compared to traditional components even if it was recognized that different indicators are needed for their evaluation:

> *"So many people still doubt the technology, cannot see the benefits. Everything has to start from the design. It would not be so hard to understand if AM were another standard production machine, only a bit more effective, so it would be easy to see that the part was done a lot faster and then the costs are these. But we have to understand that we get a better design, which affects the customer value, or a component can deliver better performance and because of that we can put a bigger price tag on it."* (Cluster 3, Company O).

Satisfaction with the status quo can hinder experimentation when adopting AM technologies. The interviewees, particularly in OEMs, subcontractor firms, and industrial design firms, expressed that they do not have time to learn the new technology; they use traditional advanced manufacturing equipment that delivers great performance. The companies' competitiveness relies on that efficiency, as well as traditional materials, and the quality of their end products are well known and satisfy customer needs. AM production would require new competences on new materials, new design paradigms, new AM processes, and new testing methods, and this learning curve is considered too expensive and time consuming for SMEs.

The *external challenges* were not as easy to code in terms of the interviewees' experiences, and some of the challenges now classified as external could also belong to the strategic and supply chain categories. Lack of inspiration from other examples was recognized in all firm types, and this may be more a company-specific challenge than reflecting a particular supply chain position. Subcontractors experienced the most external challenges to adopt AM by investing in AM machinery, for two reasons: 1) they do not have secure orders for AM and they cannot invest unless there are orders for AM, and 2) they are afraid of competition, i.e., larger companies or OEMs investing in their own AM machines. An interviewee in a subcontractor firm stated: "*Not a single customer has ever asked us anything about AM capabilities, and then, if they ask, we have to think about it*." (Cluster 2, Company B). Interviewees in OEMs, in turn, said that they are not willing to invest in their own AM machines if they can use a subcontractor, but their subcontractors have not offered them any ideas about leveraging AM. This indeed may be a strategic challenge, as explained by one of the interviewees: "*We do not have enough knowledge to ask about AM from subcontractors and discuss it. AM is such a new technology, even if we have carried out a few experiments. But in a way, if the subcontractor would comprehensively begin to go through what potential 3D printing would offer to this particular product, we could definitely consider AM as an option*." (Cluster 1, Company K).

Table 4 summarizes the key challenges identified and the comparison across the four clusters of SMEs, based on the mapping of interviewees' experiences of AM adoption. The data indicates that all kinds of challenges are experienced by the SMEs, but to somewhat varying extents. There are evident differences across the SMEs' supply chain positions in which kinds of challenges dominate and how.

Table 4. Identified challenges in adopting AM and comparison of different company clusters.

	Type of company			
Challenges in adopting AM	**OEMs n=5**	**Subcon-tractors n=4**	**AM service providers n=3**	**Designers n=5**
Technology-related: AM technology and material uncertainties				
Distrust of materials, AM parts' quality, durability, and process standardization	**3**	**2**		**3**
Long production time and limitations regarding the size of a component	**2**	**1**		
Immaturity of AM technology/rapid development of AM technology	**2**		**1**	
No standards amongst different AM machines/different brands of machinery require special skills	**1**		**2**	
Costs/lack of cost calculation models	**2**			
Need for post-processing and resulting costs		**1**		
Missing certifications/standards	**1**			
Strategy-related: Strategy and economic situation				
Lack of enterprise-wide strategy for AM/willingness to adopt	**1**	**2**	**1**	
AM technology is an expensive investment	**1**	**3**		
Competitors are hesitant to adopt AM	**1**	**1**		
Recession in orders, no willingness to invest in a bad financial situation		**1**		
Supply chain-related: Digital data transfer, software				
Uncertainty of the emerging supply chain structure	**1**	**3**		
Reliable data transfer, quality, and accuracy of the design file are insufficient		**2**		**2**
Full digital design chain from the designer to machine operator does not yet exist or is incomplete		**2**		**2**
Undeveloped and expensive calculation and simulation software, no material models of AM		**1**		**2**
Paper designs/blueprints are still the industry standard		**2**		
Operational: Design, R&D, innovation				
Right parts/applications for AM productions have not yet been identified	**5**	**1**	**2**	**2**
Current production parts are not suitable for AM production	**1**	**2**	**2**	**1**
Designers' weak knowledge of production and post-processing		**2**	**1**	**1**
Overall optimization using the potential of AM is challenging	**1**		**1**	
Lack of availability of product development data from the customer				**2**
Organizational: Current skills and practices; lack of knowledge				
Limited/lack of knowledge about AM technology and design	**4**	**2**		**3**
Current production machines deliver great performance	**4**	**2**		**1**
The difficulty of perceiving the benefits and applications	**2**	**3**		**1**
Learning all the new skills required is too time consuming with current workload	**1**	**3**		**1**
Production indicators/metrics lean strongly towards traditional manufacturing		**2**	**1**	**1**
External: Customer and subcontractor relationships and marketing				
Lack of inspiring examples and applications	**2**	**1**	**1**	**1**
No existing or assured orders for new machines		**3**	**1**	
Customers have not made any requests about AM capabilities		**2**		**1**
Customer R&D does not take AM method into account when designing parts		**2**	**1**	

Product protection is challenging, and appropriate agreements are missing				2
Customer’s management does not have a full picture about AM technology and its possibilities			1	
Subcontractors do not see the potential of AM or have not taken the initiative	1			

Note: Numbers indicate how many companies experienced the challenge in the cluster.

Among the studied companies, only the service providers have AM machines in-house. Interviewees in the service provider firms stated that they need to do a lot of marketing, customer convincing, and education since they lack industry contacts (in line with Mellor et al., 2014), because their customers’ management does not fully understand AM technology and its possibilities. There were some general key differences between the companies in different supply chain positions, regarding interest in investing in or sourcing AM capacity. OEM companies considered both perspectives, and they were most uncertain about AM technology. Subcontractors mostly considered investing in machinery, or alternatively being one part of the supply chain, conducting post-processing for AM service providers. They experienced various challenges rather similarly across the categories, and supply chain-related challenges were emphasized. AM service providers relied upon their customers’ acceptance to adopt sourced AM components and depended on their partner network as an important driver in AM-related decisions. They experienced the most challenges in cooperation (operational and external), such as educating, marketing, and designing with their customers to deliver enough value. Industrial designers also relied on their customers’ acceptance of AM, and expressed facing the most challenges in the design process. They had very clearly experienced the customers’ habit of sticking to old practices, and the lost opportunities to redevelop products for economic or customer relationship reasons.

4.2 Requirements for promoting the adoption of AM in SMEs

Interviewees pointed out different requirements for promoting AM in their firm and supply chain, and these requirements often dealt with multiple challenges. The requirements were divided into five categories through an inductive analysis: AM technology, knowledge, strategic decision, digitalization, and cooperation.

Table 5. Requirements for adopting AM and comparison of different company clusters.

Requirements \ Type of company	OEMs n=5	Subcontractors n=4	AM service providers n=3	Industrial designers n=5
AM technology AM technology and processes need to advance; the right application needs to be found for AM manufacturing	**4**	**1**	**1**	**3**
Knowledge Specific type of knowledge is needed to adopt AM	**5**	**4**	**3**	**4**
Strategic decision Strategic decision-making is needed to initiate AM adoption			**2**	**2**
Digitalization Some specific digitalization advances are needed to promote AM adoption		**3**		**2**
Cooperation Some kind of cooperation is needed, as most of the SMEs cannot compete on the AM market with their own resources alone	**1**	**3**	**2**	**3**

Note: Numbers indicate how many companies mentioned the requirement in the cluster.

Prior research has already collected most of the *technological and AM process*-related requirements for improving the expansion of AM manufacturing, which can be seen in Gausemeier and Echterhoff's (2013) study. Despite the technical limitations and iterative progress of AM technology, nine of the interviewees said that AM is already applicable, standards are being created for AM, and technology as such can no longer be seen as an implementation barrier. Investments and innovation are needed to overcome the challenges, and it may mean research and/or development. For example, one interviewee pointed out the need for research funding: "*Somebody needs to finance material research in order to develop calculation models for designs and simulations. After that, industrial designers can really start leveraging AM in challenging applications.*" (Cluster 4, Company L).

In order to find the right applications, companies need more *knowledge* about AM. Most of the interviewees expressed that their company management is aware of AM manufacturing, but more information is needed about the principles, and more know-how, education, and training are required, especially concerning AM technology and manufacturing. The knowledge requirement was strongly evident in companies in all supply chain positions. The interviews mostly concerned product-level AM, only superficially mentioning process and production levels. According to the interviewees, more information is needed about the production and supply chain benefits and trade-offs of adopting AM. One interviewee emphasized the strategic aspects of this knowledge: "*At this point, the most important thing is to educate decision-makers in OEM companies—they need to realize all of the benefits of AM, not just concerning the product but also production. After that, designers may get enough resources to start making use of AM.*" (Cluster 4, Company P).

SME management has to realize the potential strategic benefits of supporting the designers and production in adopting AM by creating a company-wide strategy to properly use AM in their business, and the requirement of *strategic decisions* appeared particularly central among service providers and industrial designers. Even if OEMs and subcontractors did not express strategic decisions as a requirement, they found the lack of a strategy as a challenge, which implies that it is also important. Service providers and industrial designers recognized that their customers (i.e., manufacturing firms) need a strategic decision to start using AM comprehensively. As AM differs so much from traditional manufacturing technology, the adoption should start with strategic management. Designers have the capability to learn this new manufacturing method, its benefits, and limits, if they get the resources and encouragement they need from management.

Regarding strategy, the interviewees particularly discussed the products to be manufactured using AM, and that the customers are ready for new kinds of products. As one interviewee explained: "*Customers need to learn and become accustomed to the price level, and therefore find the products where value can be added to justify a higher price.*" (Cluster 1, Company I). Interviewees pointed out that AM can either replace traditional production, or enable the creation of completely new kinds of offerings, and decisions concerning this are highly strategic in SMEs. Where AM replaces traditional production, the products have more or less the same design. The replacement approach would require that machine and material prices drop, the speed of the AM machines increases, customers order, and cooperation with customers increases. Creating new offerings for AM implies identifying a completely new way to create customer value, and designing and producing completely novel components or products. This novelty approach would require that a company takes the risk of investing heavily in R&D, finds a sufficient customer base with unique needs, and has a strategy for designing innovative products that can create bigger customer value. Although the AM components may cost more than ordinary components, their novelty and added value justify the cost. According to one interviewee: "*Certain applications will certainly bring a great deal of added value, especially for products that could not otherwise be manufactured. The role of designers has to be emphasized.*" (Cluster 2, Company J). The company could also try to find assemblies where AM could be used for integrating multiple components (i.e., offering a more complete solution to customers), resulting in significant supply chain and cost benefits. Both in the replacement approach and novelty approach, it is crucial to find the right applications and components for AM manufacturing.

Some of the supply chain and data transfer challenges can be overcome by introducing *digitalization*, which may mean implementing a high-quality data transfer standard as well as toleranced 3D CAD models throughout the supply chain. With increased supply chain digitalization, subcontractors could decide the most suitable manufacturing method for a given product, which could then enable reliable quality control in the process. This is done by measuring or scanning a finished product and comparing that to a toleranced CAD model, revealing the dimensional accuracy. Quality control of microstructures has to be embedded into the building process, which will probably be solved as technology advances.

> *"Industry standard currently is STEP-203, but it is a poor standard. The whole industry network should start using STEP-242 as soon as possible, from where we can get all that knowledge that we really need about the features of geometric elements, including all the tolerances and surface roughness, to essentially determine how it is to be manufactured. So more complete data transfer is required."* (Cluster of subcontractors, Company B).

Currently, there is no established *cooperation* model for AM manufacturing between companies, which was said to be an important factor to facilitate finding the right people and capacity. Therefore, cooperation models should be created through the supply chain. With little direct demand for AM products in the domain of machine manufacturing and process industries (i.e., outside major AM application industries), SMEs in this sector have to bravely conduct experiments, understand how customers' needs could be met with AM, and take a proactive role in creating demand. Investing in cooperation with AM service providers was experienced as an advantage. "*Customer relationships should be more transparent and based on trust or good contracts, because information restrictions hinder the design process.*" (Cluster 4, Company D).

5. Discussion

5.1 Holistic view of the adoption challenge: AM as a systemic innovation

In the first research question, we inquired: "How do SMEs in different supply chain positions differ in their challenges in adopting AM?" The findings of this exploratory study offer evidence that all AM implementation factors in Mellor et al.'s (2014) framework present challenges concerning AM adoption. Compared to studies of large firms (Flores Ituarte et al., 2016b) and mixing large firms and SMEs (Gausemeier and Echterhoff, 2013; Niaki and Nonino, 2017; Deradjat and Minshall, 2017), we have unveiled the specific nature of SMEs' AM adoption, and specifically offered initial empirical support for the centrality of partner orientation in SMEs (Deradjat and Minshall, 2017).

Exploring different types of companies reveals all kinds of challenges (Table 4), shows a different combination of challenges for SMEs in different supply chain positions, and therefore adds to previous studies that are often restricted to a certain supply chain position (Table 2). Recently, only Muir and Haddud (2018) have compared supplier and customer challenges in AM adoption, and none of the previous research has covered the AM adoption challenges across different supply chain positions. The findings show that SMEs in different supply chain positions experience similar operational and external challenges, while experiencing different technology, strategy, supply chain, and organizational challenges. One possible explanation for the differences may stem from whether the SMEs plan to invest in AM machinery or source AM from service providers. Also the broad range of different SMEs, each with their unique technology, strategy and innovativeness features, will likely have an effect on the firms' AM adoption even within the same supply chain position, which has been suggested in previous research concerning the adoption of traditional advanced manufacturing technologies (Thomas et al. 2008). Especially within subcontractor firms and OEMs, it was noted that different companies had quite a different approach to technology utilization, ranging from static and low-technology to more dynamic and development oriented. Among the companies in this study, only the service providers could be considered as high-tech companies in the context of AM.

The importance of digitalization was highlighted in the interviews as an element of supply chain-related challenges, especially amongst subcontractors and industrial designers. The findings provide empirical evidence concerning a recent prediction (Oettmeier and Hofmann, 2017) that using AM for industrial components production requires a higher level of integration in information technology systems and process flows. The finding on the uncertainty of supply chain structure as an AM adoption challenge also lends support to an earlier proposition that a special focus should be given to supply chain-related issues (Oettmeier and Hofmann, 2017).

The findings have offered evidence of the generally challenging nature of adopting AM in a new sector, namely the machine manufacturing and process industries. While previous research has centered on early adopters and straightforward supplier–customer relationships (e.g., Rylands et al., 2016), our findings portray AM adoption as a supply chain issue since the machine building sector is accustomed to collaborating with a variety of subcontractors and service providers. We have shown that the successful adoption of AM would require time and effort across the supply chain, and finding solutions to each supply chain actor's specific AM adoption challenges. Based on these findings, we propose the following:

> **Proposition 1.** The benefits of AM on a large scale will likely be reaped in the context of machine manufacturing and process industries if the entire supply chain adopts AM technology and its consequences.

In the scope of this exploratory research, AM seems to display some features of a systemic innovation, i.e. innovation "whose benefits can be realized only in conjunction with related, complementary innovations" (Chesbrough and Teece, 2002, p. 128). Our study focused on machine manufacturing and process industries that have a tradition of using subcontractors and external services in their value chain. In this context, it was not self-evident which firm should own the AM machines, and as the technology influences the value chain from customer needs analysis and design to manufacturing, AM innovation has to spread throughout the network to start working properly, and in line with Steenhuis and Pretorius (2017) the levels of innovation may vary. Muir and Haddud (2018) have also recognized the importance of system-wide AM adoption.

5.2 Solutions and actions to overcome the adoption challenges in the supply chain

The second research question asked: "How can SMEs overcome the challenges?" Our analysis yielded five themes of requirements for AM adoption, and some differences were identified among the various supply chain positions. The requirements to solve technology challenges, add knowledge, and activate cooperation were experienced fairly consistently across companies in different supply chain positions, whereas digitalization was requested by subcontractors and industrial designers, and strategic decision making was expected from manufacturing firms. We divided the actions to overcome the adoption challenges into strategic actions and operative actions.

The interviews revealed a need for AM strategy, particularly among the customers of the service-centric and industrial design firms, to promote AM adoption. This finding lends support to Steenhuis and Pretorius (2017) who link the use of selected process technologies with certain (strategic) performance objectives. The interviewees also recognized inter-company cooperation as a requirement for AM adoption in SMEs, which offers empirical evidence in support of previous research. Oettmeier and Hofmann (2016) proposed that a focal firm's engineers and the contract manufacturer's production department would need to closely interact to create successful components and make fast product design changes. Deradjat and Minshall (2017) found that a firm's smaller size forces it to collaborate. In order for SMEs in any of the supply chain positions to be able to create demand for AM components, they would need to cooperate with some lead customers and develop innovative prototypes to demonstrate the benefits of AM to other customers. If the firm sources AM components, it can start activating potentially interested partners in the supply chain. Partnering may involve other kinds of organizations, too. Our findings indicated that some SMEs initially adopted AM through involvement in government-funded research projects, in line with earlier research (Deradjat and Minshall, 2017; Rylands et al., 2016). Based on these findings, we propose the following:

Proposition 2. To advance the progress of AM, SMEs should take strategic actions to overcome the challenges in AM adoption, including:

- developing strategies by identifying the benefits of AM, selecting the focal application areas, and deciding on "make or buy";
- scouting and collaborating to accumulate AM information, and advancing digitalization;
- starting with lead customers, creating demand through prototypes, and activating supply chain partners.

The findings concerning operative actions showed that SMEs need new knowledge and technological advances to solve various technological and material uncertainties, including quality problems. Requirements of knowledge and skills have been pointed out in recent research as well (Murmura and Bravi, 2018), and our findings suggest a need for learning through research and active experimentation as operational actions towards the adoption of AM. Deradjat and Minshall (2017) discovered that the poor quality of metal AM parts in the beginning of AM diffusion created a negative image that still exists as a prejudgment that AM does not meet the necessary requirements. Therefore, technological advancement needs to be complemented by active efforts to improve AM's image, for instance by educating customers and other companies in the supply chain on working with AM. Besides separate education efforts, sufficient resources should be given to designers to learn and experiment, so that they can incrementally move from small-scale AM pilots towards the ramping up of full-scale AM deliveries in selected niche products and markets. This of course requires that the SME's management sees the benefits of AM. Furthermore, our findings showed that SMEs need to overcome the hurdle concerning the performance strengths of traditional manufacturing, and tolerate AM's learning curve. This potentially means that the SMEs should create new assessment criteria and metrics that take AM into consideration when monitoring business performance. Based on the findings, we propose the following:

> **Proposition 3.** To advance the progress of AM, SMEs should take operational actions to overcome the challenges in AM adoption, including:
>
> - reducing technical and material uncertainties through learning, small-scale experiments, and research;
> - giving resources to designers to learn and experiment, scaling up AM deliveries in selected niche products and markets; and
> - creating new assessment criteria and metrics for AM manufacturing.

6. Conclusion

The analysis of managers' experiences in four different types of SMEs revealed a variety of challenges and some clear differences, according to the firms' supply chain positions. Where OEMs and subcontractors struggle with technology, strategic decision making, and organizational issues, service providers and industrial designers face various operational, organizational, and supply chain issues that possibly relate to their customers' choices and knowledge. Overall, a supply chain setting may in fact pose a major barrier to diffusing AM in the industry. By mapping the challenges and pointing out the importance of supply chain position across different firms, this study contributes to the literature on AM adoption through evidence specific to SMEs and metallic AM in the machine manufacturing and process industry context.

Besides understanding the variety of challenges, the goal was to identify the requirements in adopting AM across the supply chain, and develop new knowledge on the practices that are needed to promote AM adoption. As technology-related requirements and actions have already been covered, we focused on the socio-economic factors that need to be resolved to overcome the challenges in AM adoption. The identified requirements set out a development agenda for SMEs if they want to benefit from AM in their business. Our results showed somewhat different development priorities between the supply chain positions in that service firms (AM service providers and industrial designers) set certain expectations for manufacturing firms as their customers, and manufacturing firms in turn need to decide whether to "make or buy" regarding

AM capacity. Although we proposed certain general actions to drive the advancement of AM adoption, the industrial field is still open to a first-mover advantage—at least in the context of the companies in this study.

The findings in this study offer practical possibilities for SMEs to position themselves in the versatile supply chain alternatives, and map their AM adoption challenges in comparison to others. As we also pointed out specific requirements experienced by SMEs as prerequisites for AM advancement, other SMEs could also find these requirements useful when defining their learning tasks and roadmaps for AM adoption, and in action planning. Large companies may also use the framework of AM adoption challenges and themes when involving their subcontractors in AM-related transformation. Furthermore, the findings may act as a starting point for education providers to identify and prioritize AM-related learning content to educate manufacturing firm personnel.

This study has revealed the systemic nature of AM technology innovations, implying that SMEs and large firms cannot develop their AM capabilities in isolation. Thereby, the findings of this study are relevant to national innovation systems across countries. As digitalization of manufacturing industries is underway in different countries, SMEs will need broader networks and support, to adopt AM and promote related changes in their business networks. Novel R&D programs and networking instruments may be needed, to promote AM adoption in different domains, including machine and process industries. Alternatively, neglecting the systemic nature of AM technologies may slow down or fully hinder the technology adoption.

The exploratory research design has offered a broader perspective on SMEs' experiences than single or comparative case studies, but it also has limitations. The SMEs in this study are from machine manufacturing and process industries, thereby limiting the findings to this context and to the early phases of the AM adoption process. We purposefully excluded large firms, which creates another limitation. At the same time, we drew attention to multiple different positions in the AM supply chain. In the future, full supply chains and their different actors should be studied in relation to each other, and different firms' expectations in the specific supply chains should be explored.

Qualitative interview data and the selection of informants may cause validity limitations, of which we are aware. We chose the interviewees among SME managers who know their firms' strategic priorities, so that they would be knowledgeable informants regarding the prospects of AM adoption. We also had multiple firms and informants concerning each specific supply chain position, and this approach was expected to alleviate the concern for potential respondent bias. We also explicated the interview protocol and analytical procedures to offer transparency. It is possible that some validity concerns may persist despite these practices, and we propose developing the AM adoption challenges and requirements into a questionnaire survey and testing the findings in broader questionnaire studies, covering different companies in supply chain positions, industries, and phases of AM adoption. To achieve a complete picture of supply chain-level challenges, we propose carrying out in-depth case studies at the level of AM supply chains, to complement the previous studies concerning only certain manufacturing firms.

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Supply chain innovations for additive manufacturing

Toni Luomaranta and Miia Martinsuo

Department of Industrial Engineering and Management,

Tampere University, Tampere, Finland

Abstract

Purpose: Additive manufacturing (AM) involves the renewal of production systems and also has implications for firms' supply chains. Innovations related to AM supply chains are, so far, insufficiently understood, but their success will require firms' awareness of their systemic nature and their firm-specific implications. The purpose is to explore the supply chain innovations dealing with AM in business-to-business supply chains.

Design/methodology/approach: An exploratory qualitative research design is used. Interviews were conducted in 20 firms, workshops were organized to map AM-related processes and activities, and supply chain innovations were analyzed.

Findings: This study reveals practical changes in supply chains and requirements for AM-related supply chain innovations. While earlier research has centered on technology or firm-specific AM implementations, this study shows that fully leveraging AM will require innovations at the level of the supply chain, including innovations in business processes, technology, and structure, as well as supportive changes in the business environment. These innovations occur in different parts of the AM supply chain and are emphasized differently within different firm types.

Research limitations/implications: This research was conducted in one country in the context of the machine building and process industry with a limited dataset, which limits the generalizability of the results. The results offer an analytical framework and identify new research avenues for exploring the innovations in partial or complete AM supply chains.

Practical implications: The results offer a framework to assess the current state and future needs in AM-related supply chain innovations. Practical ideas are proposed to enhance AM adoption throughout firms' supply chains. These results are important to managers because they can help them position their firms and guide the activities and collaborations with other firms in the AM supply chain.

Originality/value: This study draws attention to the supply chain innovations required when firms adopt AM in their processes. The generic supply chain innovation framework is enhanced by adding the business context as a necessary component. Implementation of AM is shown to depend on the context both at the level of the supply chain and the firm's unique role in the supply chain. The holistic view taken reveals that successful AM technology adoption requires broad involvement from different firms across the supply chain.

Keywords: Additive manufacturing, manufacturing technology, supply chain innovation, radical innovation

Introduction

Additive manufacturing (AM) implies the use of digital product designs and a process of joining and adding layers of material (ASTM, 2012) to produce goods. It can challenge traditional removal and molding-centric manufacturing and either revolutionize entire processes (D'Aveni, 2015; Weller *et al*., 2015) or complement traditional manufacturing (Holmström *et al*., 2016; Rylands *et al*., 2016; Sasson and Johnson, 2016). Earlier conceptual studies showed that AM has great potential to enhance operations. For example, with AM, almost any shape can be manufactured without tooling, which allows parts to be made independently at no extra cost. This can potentially simplify supply chains, shorten lead times, and reduce inventories, consequently enhancing flexibility and improving customer satisfaction (e.g., Holmström *et al*., 2010; Weller *et al*., 2015). The majority of previous research has focused on AM in single large early adopter firms in consumer goods industries, whereas less is known about the possibilities of AM more broadly in supply chains in business-to-business industries and the involvement of small and medium-sized enterprises (SMEs).

This paper focuses on the supply chain innovations concerning AM in industrial firms' supply chains. Supply chain innovation represents the possibility for manufacturing firms to enhance their competitiveness by changing their supply chain network, technology, process, or a combination of these (Arlbjørn *et al*., 2011). Implementing AM can have a significant effect on manufacturing firms' supply chains (Holmström and Partanen, 2014) and potentially requires the re-engineering of business logics (Weller *et al*., 2015). Each firm may have a very different role in the supply chain, and it is not yet clear which firms should implement AM, how their partners can support AM adoption, and what kinds of structures will emerge for AM supply chains (Rogers *et al*., 2016).

Implementing AM technology not only affects the firm using AM machines for producing goods, it changes the supply chain process and requires involvement in the upstream of the supply chain. Additive manufacturing requires specially processed raw materials (Khajavi *et al*., 2014), which requires the involvement of raw material manufacturers. Designers need to consider the new production process during the product development and design stages (Martinsuo and Luomaranta, 2018). After AM, , parts need post-processing (Khajavi *et al*., 2014) before product assembly or final use. Although this could be done by the AM machine operator, it could involve another firm, machine shop, or similar, that has a large variety of traditional machining equipment (Strong *et al*., 2018). This implies that AM could influence the downstream supply chain.

For example, a machine shop with traditional manufacturing equipment and methods based on paper blueprints now has to convert to very accurate material removal from an almost-finished part based on a digital file. Previous studies have generated a conceptual illustration for the metallic AM supply chain (Holmström *et al*., 2016) and an empirical illustration of a business-to-consumer metallic AM supply chain from the point of view of a single firm (Rylands *et al*., 2016), but they do not offer empirical evidence concerning multi-firm supply chains for metallic AM in the context of business-to-business industries of machine building and industrial processes.

The purpose of this study is to explore the supply chain innovations that take place when AM is adopted in the supply chain. Firms need to respond to the changes in the business environment and take part in supply chain innovations in order to successfully complete the implementation of AM. The goal is to create knowledge about AM supply chain innovations and the related activities in the different firms in the AM supply chain. The study focuses on three research questions:

1) What kinds of contextual changes take place in business-to-business AM supply chains?

2) How—through what kinds of activities—do different firms participate in the AM supply chain process?

3) How can firms leverage AM through innovations in their supply chains?

To address to these questions, this study focuses on industrial goods manufacturing and, more specifically, on firms with different roles in the AM supply chain.

The paper reviews previous research on AM as an innovation in manufacturing systems, supply chain innovations, and related activities and roles of firms involved in them. The exploratory research approach, the interview and workshop data focusing on AM in the machine and process industry, and the data analysis approach are then introduced. The findings include mapping of the relevant contextual changes when implementing AM, a categorization of phases in the AM supply chain process, and required supply chain innovations. Finally, the contributions are discussed in light of previous literature and a conclusion is provided. This study contributes to the existing knowledge by revealing the contextual changes in the industrial inter-organizational supply chain during the implementation of AM, suggesting context as a necessary component in forthcoming analyses of supply chain innovations, and identifying various means that firms can use to enhance their operational efficiency through the AM supply chain. The results offer evidence that understanding AM through supply chain innovations can help firms connect with other firms in the supply chain and thus leverage AM more effectively. As practical contributions, these results help managers position their firms, guide the activities and collaborations with other firms in the AM supply chain and enhance AM adoption by means of supply chain innovations.

Literature review

Additive manufacturing as an innovation in manufacturing firms

Innovation, in its classical sense, means the introduction of a new good, feature, or method of production, the opening of new markets, the acquisition of new material sources, or the implementation of a new organization in an industry (Schumpeter, 1934). Innovations can be divided into incremental and radical changes (Freeman and Soete, 1997), and their classification depends on the innovation adopter's perspective (Johannessen *et al*., 2001). Innovations can be divided into intra-organizational and inter-organizational (Santosh and Smith, 2008), and they must aim to create new value (new products, services or structures) (Arlbjørn *et al*., 2011). In this study we focus on inter-organizational innovations specifically dealing with AM.

Additive manufacturing represents a radical innovation in terms of manufacturing technology (Oettmeier and Hofmann, 2016; Rylands *et al*., 2016), and in many cases AM technology advancements have been seen as enablers of new benefits in products, batch sizes, and waste reduction (Holmström *et al*., 2010). These and later studies called AM a groundbreaking innovation, where AM technology has pushed the implementation, but regarded it as a complementary innovation for the manufacturing industry or its supply chains (Oettmeier and Hofmann, 2016; Rylands *et al*., 2016; Steenhuis and Pretorius, 2017; Durach *et al*., 2017).

There are indications that a single firm cannot achieve the full benefits of AM alone and that AM adoption requires the involvement of multiple stakeholders in the supply chain (Oettmeier and Hofmann, 2017). *Supply chain* in this study is defined as a network of firms that transfer and process materials and information between them to create value (Heikkilä, 2002). Adopting AM technology might affect the interactions between supply chain firms (Durach *et al*., 2017) because firms' roles in the supply chain may change, new firms may enter the field with completely new capabilities, and some current supply chain relationships may be substituted by new AM-specific relationships (e.g., AM material suppliers, service providers, designers). Previous research suggests viewing AM as a systemic innovation that requires complementary innovations to achieve the expected large-scale benefits (Martinsuo and Luomaranta, 2018).

Supply chain innovations and required activities

Manufacturing firms often operate in networks of firms that need to collaborate to produce a product or a service, and to innovate (Manceau *et al.*, 2012). The concept of supply chain innovation deals with firms' innovation efforts to achieve a competitive advantage through and for their supply chain by developing operational and service efficiency and increasing both the firm's revenue and the supply chain's joint profits (Bello *et al.*, 2004). Supply chain innovation can be defined as "a change (incremental or radical) within a supply chain network, supply chain technology, or supply chain process (or a combination of these) that can take place in a firm function, within a firm, in an industry or in a supply chain in order to enhance new value creation for the stakeholder" (Arlbjørn *et al*., 2011, p. 8).

Supply chain innovations take place through a series of activities that help a firm deal with uncertainty in its business environment, respond to its customer demands, and enable more efficient supply chain management (Lee *et al.*, 2011). Supply chain innovation can therefore be used as a tool to enhance supply chain performance through interaction with up- and down-stream supply chain firms (Lee *et al*., 2014) and creation of collaborative relationships, especially when implementing new technologies that can be beneficial to several firms in the supply chain (Storer *et al*., 2014).

According to Bello et al. (2004) and Lee et al. (2011), supply chain innovations are operationalized through a set of activities, which can be divided into multiple categories. Two conceptual studies (Bello *et al*. 2004; Wong and Ngai, 2019) identified similar categories with a sales-oriented focus. Arlbjørn *et al*. (2011) identified three categories with a focus on operations management: 1) supply chain business processes, 2) supply chain technology, and 3) the supply chain network structure. The empirical study of Munksgaard *et al*. (2014) noted that supply chain innovations can originate from any of these three categories separately or combined. Due to our focus on AM supply chains directly dealing with manufacturing systems, we will build on the supply chain innovation framework of Arlbjørn *et al.* (2011).

Previous empirical studies have examined supply chain innovation activities in consumer goods manufacturing, specifically hearing instruments and shoe manufacturing (Munksgaard *et al*., 2014), and car manufacturing and pharmaceuticals (Ageron *et al.*, 2013).

Most of the earlier supply chain innovation studies have focused on analyzing the individual and organizational level of supply chain innovations (Wong and Ngai, 2019), implying a further research possibility concerning the inter-organizational level. Supply chain innovations are also considered as very context dependent and cross-organizational (Ojha *et al.*, 2016), which suggests a research gap, as supply chain innovations have not been covered in business-to-business settings, specifically in the context of AM.

Supply chain innovations for additive manufacturing in different types of firms

Two supply chain types are particularly relevant in the AM industry. The first type concerns AM equipment, proceeds from the machine supplier to the machine owner and user, and involves project business. The second type concerns goods manufactured using AM equipment, is product business, and extends from material suppliers through AM manufacturers and their design and software partners to their customers and other suppliers (Mellor *et al.*, 2014). In this study, we focus broadly on product-related supply chains.

Supply chain innovations have not been covered purposely for AM, but their indications appear in some previous studies. Many conceptual studies summarize the possible impacts of AM implementation on supply chains (Holmström *et al.*, 2010; Petrick and Simpson, 2013; Steenhuis and Pretorius, 2017; Sasson and Johnson, 2016). The nature of AM (with improved product-level integration) can enable simpler supply chains, shorter lead times, and lower inventories, likely resulting in cost reductions (Holmström *et al.*, 2010). Reliance on digital designs can shorten and simplify physical sections of the supply chain (Campbell *et al.*, 2011). For example, an assembled multi-component part can be digitally modeled and manufactured as a complete part with AM. This single-step manufacturing could reduce the physical transportation needs, which would have an impact on inventory and logistics costs (Holmström *et al.*, 2010; Holmström and Partanen, 2014).

Only a few empirical studies have taken supply chain impacts into consideration (Rogers *et al.*, 2016; Rylands *et al.*, 2016; Thomas, 2016; Oettmeier and Hofmann, 2016), they are summarized in Table 1, and these have typically emphasized the viewpoint of large firms or a single SME, not a complete supply chain. AM is a rapidly emerging industry where service providers are gaining a foothold (Rogers *et al.*, 2016), and smaller firms need to rely on their networks when they are adopting AM (Martinsuo and Luomaranta, 2018).

Table 1. Summary of previous empirical research on AM-related supply chain innovations

Source	**Context and method**	**Findings on supply chain innovation activities**	**Gap or motivation driving this study**
Oettmeier and Hofmann, 2016	Impact of AM adoption on supply chain management, two case studies (plastic AM from the hearing aid industry), SME firms operating their own AM machine	Processes such as order fulfillment, manufacturing, and supply chain management are affected by the adoption of AM	Future research should study the relationships between firms in the AM supply chain
Rogers *et al*., 2016	3D printing services, evaluation of 404 3D printing service providers' offerings, different service providers (AM machine operators and AM designers)	Different kinds of AM service models are emerging	How will the future supply chain configuration strategies, structures and operations change?
Rylands *et al*., 2016	Value stream changes after the adoption of AM, two case studies (consumer products), metallic AM, two small firms producing filters and wallpapers, sourcing AM manufactured parts	AM changes the value stream so customers can engage in the design process better than before	Supply chains are areas where AM could cause disruption and change
Thomas, 2016	Comparative single assembly supply chain cost analysis, metallic AM, car steering systems as a whole assembly	AM affects both manufacturing process level and system (supply chain process) level	How will the whole supply chain benefit from AM?
Martinsuo and Luomaranta, 2018	Adoption of AM in the SME sector, exploratory research, metallic AM, 19 SME firms from supply chains in the machine building and process industry	SMEs rely on their networks when adopting AM	What kind of innovations could complement AM adoption?

Many of the benefits expected of AM assume that some supply chain innovations take place during AM adoption. Manufacturing firms should therefore consider the potential effects of AM on supply chain processes and management both within the firm and in partner firms (Oettmeier and Hofmann, 2016). For AM to fully deliver its potential, it is argued that such process technology innovations require restructuring of the relationships with suppliers and customers, increasing collaboration (Mellor *et al*., 2014).

Some production features in the current AM technologies need to be considered to reach the volume-related benefits of AM and may potentially be resolved through supply chain innovations. In AM technologies, manufacturing capacity does not refer to the number of components but rather to the building platform fill rate, meaning the amount of space a component takes up on a building platform where components are then produced. Ultimately, batches of one may not be economically feasible if the component is much smaller than the building platform (Piili *et al*., 2015). Also, AM currently has a significant need for post-processing (Khajavi *et al.*, 2014) and components need to be machined, heated, or polished after manufacturing. Therefore, AM supply chains should also consider operations and firms outside of the bespoke AM processes.

Different types of firms will have their own ways to contribute to AM through supply chain innovations. The empirical studies in Table 1 have primarily taken the perspective of certain types of firms, such as AM producers (Oettmeier and Hofmann, 2016; Rylands *et al*., 2016) or service providers (Rogers *et al*., 2016), whereas one study takes a more systemic view (Thomas, 2016) and another study draws attention to the different firms' different experiences with AM adoption (Martinsuo and Luomaranta, 2018). So-called supercenters are predicted to arise from large manufacturing firms that implement AM alongside their traditional mass manufacturing technologies to serve internal or external customers (Sasson and Johnson, 2016). Strong *et al*. (2018) propose that strategically placed AM hubs would feed AM components for post-processing to nearby SMEs that have traditional manufacturing machines. Adding AM hubs to the traditional manufacturing supply chain could promote both AM adoption and the performance of machinery SMEs by harnessing excess capacity to post-process AM components (Strong *et al*., 2018).

Research gaps

The literature review and analysis in Table 1 portray AM as an emerging manufacturing innovation that will require supply chain innovations for better performance. There is a research gap in the area of partial or complete AM supply chains as the different firms collaborate to create value through AM, making this research focus important and complementary to single-firm studies. The second research gap is in the business-to-business context of AM, as its supply chains may be more complex than those in consumer goods manufacturing. As supply chain innovations are context dependent, an AM-focused study will offer novel knowledge in connection with modern manufacturing systems. The third research gap is the context-dependent understanding of AM implementation, and for that, further knowledge is needed about the types of changes occurring in AM supply chains, the types of innovations needed for AM supply chains, and the complementarity of different types of innovations.

Research methods

Research design

This research employs an exploratory research design to study supply chain innovations in firms in different positions in AM-related supply chains. This approach was chosen because of the emergent nature of the phenomenon and limited previous research in this domain. The industry context was selected with the intention to access a complex AM supply chain—the machine manufacturing and process industry—where brand-owning manufacturers commonly use subcontractors and external industrial designers, which are very often SMEs. In this supply chain, the AM technology is metal-based AM, since mainly metallic components are used. This context is useful for the study of anticipated and ongoing changes in supply chains and the supply chain innovations needed to fully leverage AM.

Different types of firms involved in machine and process industry supply chains were enlisted through a list of technology industry firms in Finland in a region active in these industries, and by inviting the firms to participate in interviews and an AM supply chain-related workshop series. The initial list contained about 70 firms with different supply chain roles, and they were contacted by e-mail and/or telephone to seek volunteers for participation. Collecting data from different firms was seen as a means to achieve the best possible holistic understanding of supply chain innovations. The firms were selected based on their interest in AM and because they all had experience using AM or were in the adoption phase of AM technology. Altogether, 20 firms were willing to participate in the study, and this was considered suitable for an exploratory study. Alphabetical codes are used to differentiate the firms (A…U), as anonymity was promised to the interviewees during the study. Numerical codes (1…5) are used to cluster and differentiate the firm types involved in the study based on their scope of business, and to enable comparisons.

The firms vary in their supply chain roles, and different roles in potential AM-related supply chains are covered. The firms include some large firms and some medium OEMs/ODMs that can be considered to have a central position in the supply chain because they are the product users of metallic components. Most of the other firms are directly linked with the supply chains of these large/medium brand-owner manufacturing firms. Background information on the included firms is presented in Table 2.

Table 2. Background information on firms included in the study

Firm type	Firm	Approx. no. of personnel	No. of interviewees	Firms displaying additional internal document-based data	Respondents' position, total years of experience and AM experience in years	Firm experience in AM: years and specific areas
1: Large manufacturing brand owner firms	R	5000	1		Senior designer, 20+ total, 5 AM	5 years: Sources AM parts for prototyping and uses AM tooling in production
	U	45000	1	x	Vice president of technology, 25+ total, 5 AM	10 years: Has an AM machine and an AM department, sells AM products and uses AM parts in products
	S	19000	1	x	Sourcing manager, 25+ total, 7 AM	7 years: Uses AM tools in production and AM parts in products
	T	12500	1	x	AM lead designer, 10+ total, 7 AM	7 years: Has an AM machine and an AM department, uses AM parts in products and as replacement parts
2: Medium-sized manufacturing brand owner firms	A	200	1	x	Manager of production development, 10+ total, 5 AM	5 years: Sources AM prototypes for product development
	H	50	1	x	Vice president of technology, 15+ total, 5 AM	5 years: Sources AM prototypes for product development
	I	200	2	x	General manager, 35+ total, 3 AM; Vice president, 10+ total, 3 AM	3 years: Sources AM prototypes for product development and uses AM parts in products
	K	150	1	x	Manager of R&D, 25+ total, 3 AM	3 years: Sources AM prototypes for product development, planning to use AM tools in production and AM parts in products
	M	60	2		Vice president of R&D, 20+ total, 3 AM; R&D design engineer, 15+ total, 3 AM	3 years: Sources AM prototypes for product development, planning to use AM tools in production and AM parts in products
3: Small or medium sized OEMs and ODMs	B	50	1		General manager, 30+ total, 3 AM	3 years, Seeks information on how AM would influence their business, production developed to enable AM when customers ask for it
	E	15	2	x	General manager, 30+ total, 4 AM; Lead design engineer, 15+ total, 4 AM	4 years: Is post-processing parts that have been manufactured with AM
	F	160	1		Production development engineer, 25+ total, 2 AM	1 year: Is post-processing parts that have been manufactured with AM and uses AM tools in production
	J	20	1		General manager, 10+ total, 1 AM	1 year: Seeks information on how AM would influence its business

Firm type	Firm	Approx. no. of personnel	No. of interviewees	Firms displaying additional internal document-based data	Respondents' position, total years of experience and AM experience in years	Firm experience in AM: years and specific areas
4: AM service and machine operators	N	5	1	x	General manager, 25+ total, 4 AM	3 years: Has an AM machine, produces AM prototypes, tools, and parts for its customers
	Q	5	1	x	Manager of sales & marketing, 10+ total, 6 AM	4 years: Has an AM machine, produces AM prototypes, tools, and parts for its customers
5: Engineering and industrial design	C	1	1		Entrepreneur, 25+ total, 6 AM	2 years: Designs AM prototypes and parts
	D	5	1		Financial manager, 25+ total, 2 AM	1 year: Designs AM prototypes
	G	280	2	x	Vice president, 25+ total, 5 AM; Lead design engineer 15+ total, 5 AM	5 years: Designs AM prototypes, tests AM parts with its customers
	L	70	1	x	Vice president, 25+ total, 3 AM	3 years: Designs AM prototypes
	P	1	1	x	Entrepreneur, 20+ total, 5 AM	2 years: Designs AM prototypes, AM tools, and AM parts. Sells AM products

Data collection

Primary data were collected through 3 workshops and 25 semi-structured interviews in 20 firms (Table 2). Interview duration ranged from 40–108 minutes. Of these 20 firms, 13 also displayed internal documents (in-depth firm and strategy presentations), and this additional information was documented as approximately 1–2 pages of written notes per firm. Secondary data were collected from the target firms' websites to get background information about the firms and from 2 workshops to validate the results. The workshop contents and data included:

WS1 – AM value and supply chains: primary data, 18 participants, 2 pages of notes, and 4 posters

WS2 – Future scenarios: Primary and secondary data, 14 participants, and 7 pages of notes

WS3 – Future scenarios: Primary and secondary data, 12 participants, and 6 pages of notes

WS4 – New AM markets: Secondary data, 5 participants, 1 page of notes, and 3 posters

WS5 – New business possibilities: Secondary data, 5 participants, and 2 pages of notes

The interviews took place after the first three workshops. The contact persons from target firms were asked to identify a person from the managerial level with the best knowledge about AM in their firm. The interviewees were managers and directors from engineering, design, business development, sourcing, or general management (CEOs). At the beginning of each interview, the interviewees were asked whether there was another person in their firm who had better or different knowledge about AM. When another person was identified, a second interview was conducted. One additional interview was also conducted with an AM machine supplier. That interview is used as a secondary source to validate the results, together with the secondary data from the workshops.

An interview outline was formed with the help of the preliminary analysis from the first three workshops. The interview outline included questions concerning the background and position of the respondent; the firm's experience and plans for implementing AM; identified challenges in implementing AM; possible industry-specific needs for AM; opportunities to add value for the business and its customers by using AM; and production and supply chain changes required by AM. This paper concentrates on opportunities to add value for the business and its customers by using AM; and production and supply chain changes required by AM. The recorded interviews were transcribed for further analysis. After the preliminary analysis, two more workshops were organized with industry experts and firm representatives to present the preliminary results, to validate them, and to check whether anything was missing.

Data analysis

The analysis of the first three workshops took place first. Handwritten notes from the researchers were compared and rewritten analytically so each observation was retained. Posters from the first workshop represented the AM actor network and supply chain process. All four posters were compared and combined to identify a complete AM supply chain process. This is presented in Figure 1 in the Results section. Notes from the internal documents of the firms targeted for interviews were used in the further analysis of the AM supply chain process and to analyze the firms' strategic focus on that process. Each interview response was then coded in terms of whether and how the firm (i.e., a firm with a certain supply chain network role) was involved in the different phases of the supply chain process. We then cross-tabulated these results with an analysis of the internal documents, revealing the involvement of each firm in the different phases of the supply chain process. This is presented in the results in Table 4. As secondary data, the firms' websites were explored and used where possible, particularly to improve the validity of the results.

The subsequent more detailed analysis of interview data started by exploring the data and marking four themes to structure the analysis: a) How does the market change when AM is a feasible alternative? b) How does the business environment change when AM is a feasible alternative? c) Important issues in AM subcontracting, and d) Important issues for AM supply chain structure formation. Each theme's citations were inductively coded with more detail to condense the interviewees' experiences and retain the terms that the interviewees used. These findings were then pattern coded and structured thematically under two main topics: contextual changes in the supply chains preceding or after the implementation of AM (themes a and b), and required supply chain innovations (themes c and d). Pattern coding the expected changes in AM supply chains and in the business environment resulted in five categories, presented in Table 3, which includes the dominant changes in AM supply chains repeated in the interviews, explanations for these, and interviewee quotes. Changes that were expressed by only a single interviewee were excluded from the table. Since business environment changes are an important component of supply chain innovations (Lee *et al.*, 2011), this was considered an important intermediate phase in the analysis of supply chain innovations, for revealing the innovation context.

For the interview analysis, the needed supply chain innovations were grouped into innovations in supply chain business processes, technologies, and network structures, based on the thematic framework proposed in Arlbjørn *et al*. (2011), due to its appropriateness for operations management-oriented innovations and, thus, for the core focus of this study. We then mapped how each of these supply chain innovation types appeared across the different types of firms. These results were validated with the results from workshops 2 and 3. The results are presented in Table 5, which shows the categories of supply chain innovations, needed activities, example quotations, and the number of different firm types in which the innovation was expected.

After discovering the needed supply chain innovations from interviewees with the support of workshops, another analysis was performed to reveal the relations between firm types, supply chain process positioning, and supply chain innovation needs. This was done by identifying patterns from Table 4 and analyzing the reasons behind these patterns. In the findings section, we first introduce the contextual changes experienced in AM supply chains, then map the supply chain process and different firms' roles in it, and then categorize the supply chain innovations and experiences of them across different firms.

Findings

Overview of contextual changes in AM supply chains

Based on the previous literature, the introduction of AM in the manufacturing industry was expected to cause changes in the business environment, with implications for firms' supply chains. Interviewees were asked to describe what kinds of changes had already occurred and what future changes they expected in the context for AM-related innovations.

The interviewees from large firms had the most insight into how AM has changed their business environment. All four interviewees stated that their new product development cycles have shortened. Three of the four large firms had already replaced some traditionally manufactured components in their products with AM components. Interviewees from two large firms said the reason their firms' own AM machines is that AM-manufactured components are cheaper to produce. According to them, integrating multiple components into one—which was previously impossible—has made the parts and the parts production more effective. The same digital models are used throughout the manufacturing process, and the firms are planning to replicate this for other critical components, regardless of the actual manufacturing technology.

An interviewee from one large firm said that due to the tightening regulations concerning their end product, the manufacturing time for one product has shortened and the batch size has decreased. Therefore, they have given up on molds for manufacturing certain components and have started to produce them using AM. The interviewee further explained that: "About ten years ago, we had one product variant in the production for years, but nowadays we need to adjust our product every year or every two years. There is no sense anymore to order expensive molds, as the batch sizes have gotten so small it is cheaper to manufacture these small series additively. This has actually been one answer to manage the ever-tightening regulations affecting the product development in our industry" (Large manufacturing firm). This has also led to a challenge for their former logistics providers, who were not able to make small deliveries on short notice, and in some cases, some of the firm's employees had to pick the components themselves.

Even though some changes have occurred, most respondents indicated that traditional manufacturing still dominates, and operating AM technology is primarily the concern of specialized AM firms. According to one interviewee, "There are so many new areas in metal printing that it currently is not and most expectedly will not be the business of every firm" (Engineering and industrial design firm).

For this study, anticipating possible future changes was considered important, as changes may have implications for supply chain innovations. Table 3 summarizes the changes that some interviewees had already noticed in their firms' business environment and the changes expected in supply chains due to AM, grouped into five categories, further described below.

Table 3. Expected changes in AM supply chains and in the business environment

Change in AM supply chains and the business environment	**Explanation**	**Example quotations**
Digitalization of the entire design-to-manufacturing chain	Using the same digital model from the designer in every phase of the supply chain process	"The whole supply chain must start using digital plans and the key issue is to agree on roles. It must start from designing so that manufacturing can start leveraging digitalization." (Firm B)
Digitalization increasing the need for trusted business partners	Digital files and data transmission may be more vulnerable than working based on paper plans	"Trust and security are emphasized in digital services." (Firm N)
AM features complement traditional manufacturing	Changes due to "economies of one": Orders only on demand, no need for big batches to gain a cost advantage from the economies of scale	"The supply chain is going to be faster when you don't need to order big batches because of the price." (Firm D) "AM decreases the need for machining but increases the value of the machining needed." (Firm T)
Changes in operations management	Some steps will be left out from the manufacturing process, and the flexibility of batch sizes challenges traditional production management	"Of course AM will cause significant changes. Manufacturing steps are left out, quite a lot of them, I presume. And, indeed, the whole environment of the enterprise resource planning changes." (Firm A) "This will change operations management because every part can be different—it brings flexibility—but on the other hand, it can be quite slow compared to machining. There will be

Change in AM supply chains and the business environment	Explanation	Example quotations
		possibilities for new product development, testing, and ramp-up that no one has utilized yet.” (Firm G)
Changes in logistics and with suppliers	Integration of components reduces the need for logistics and multiple suppliers or changes how logistics has to be managed	“… if integration within one engine reduces the need for 855 parts to 12 parts, then it has a strong impact on supply chains and logistics.” (Firm L)

Digitalization of the entire design-to-manufacturing chain is a change that was experienced in all types of firms. It is an ongoing change enabled by recent technological developments, and an opportunity to streamline supply chains. The interviewees expressed that full digitalization increases the need for trusted business partners to be addressed in the supply chain definition and in partner selection. Also, firms that operate with traditional manufacturing technology rely heavily on their partner firms, for example, to offer research and development and post-processing capacity or services. Some of these firms act as subcontractors for other firms, and research and development for their products is initiated and/or even implemented by their customers. Two SME interviewees (B and F) said that that they had to renew their production software to be able to continue the work with their customers who required post-processing for their AM parts.

According to the interviewees, AM is a flexible manufacturing method that complements traditional manufacturing. Additive manufacturing allows production based on “economies of one,” which enables firms to manufacture orders only on demand. Consequently, the need for big batches to gain a cost advantage from economies of scale decreases. This opens up possibilities for entirely new operational models. Interviewees suggested that the small batch orientation will also lead to changes in operations management because some steps will be left out of the manufacturing process and the production type will change. This again creates an opportunity to develop operational activities and new innovations.

Changes in logistics mean there is a possibility for reduced or simpler logistics due to integrated parts. Lighter parts may also reduce costs if logistics costs are calculated based on weight. One interviewee predicted that the use of metal parts casting would decrease when AM replaces it, which means the number of suppliers may also decrease due to AM. Despite reduced logistics, the interviewees mentioned that the need to post-process components still requires transportation, since AM service providers currently do not have advanced post-processing capabilities. Therefore, it would be useful to locate post-processing firms within close proximity of AM service providers. Additive manufacturing service providers considered this to be important because part of their value promise is speed of production. With delivery times of one or two days, they cannot wait for transport for a very long time.

The AM supply chain process in the machine and process industry

The supply chain process includes the business operations across time and place, the beginning and the end, and the inputs and outputs of a supply chain (Mentzer *et al.*, 2001). Classically, supply chain processes include manufacturing raw materials, designing the product, manufacturing the product, warehousing the product, and lastly, distributing the product to customers.

To understand the nature of AM in the machine building and process industry and its specific nature, we mapped the core AM-related supply chain process. Figure 1 illustrates this process and its key activities as discovered through empirical data in the machine manufacturing and process industry, compared to a generic supply chain. This study suggests that supply chain innovations can occur in any phase of the supply chain process and across the phases.

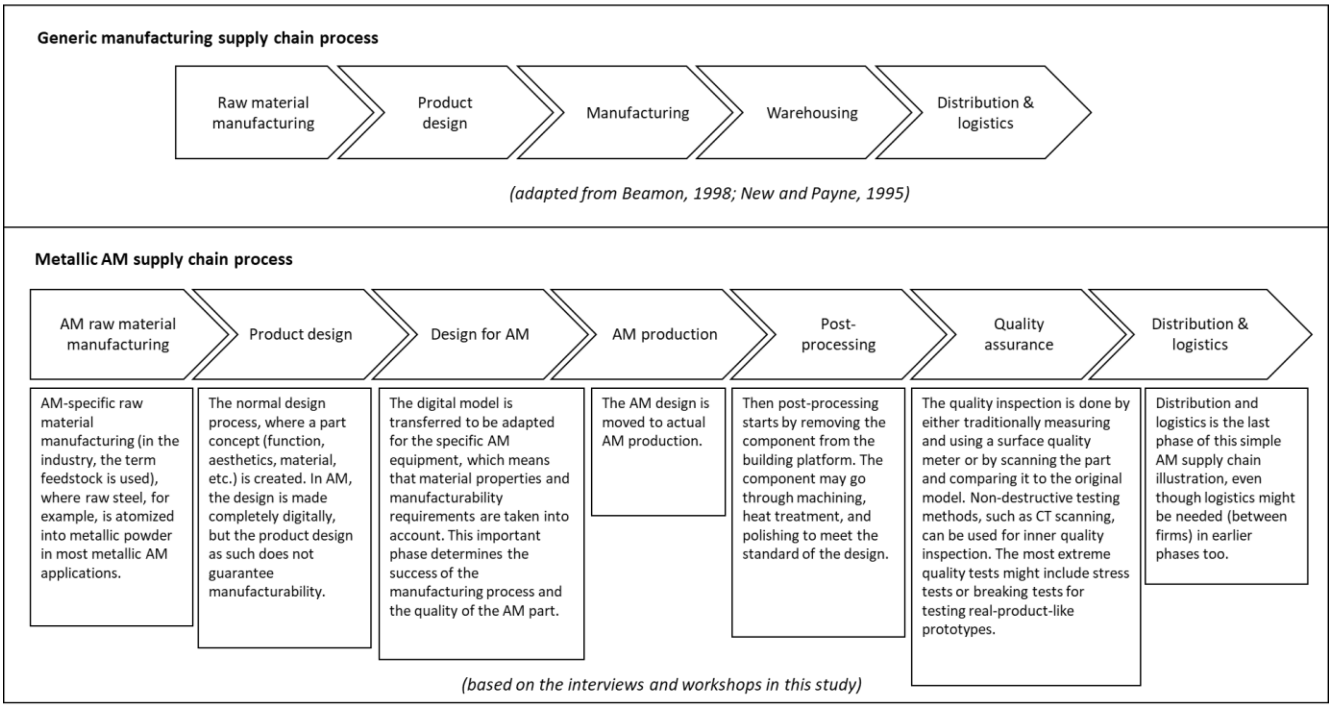

Figure 1. Comparison of generic manufacturing supply chain process with metallic AM supply chain process.

Figure 1. Comparison of generic manufacturing supply chain process and metallic AM supply chain process

After distribution, components go to be assembled in customer or OEM premises because, in the context of the machine and process industry, AM parts are mostly used as components for larger assemblies or products (such as spare parts used within a piece of equipment), instead of as final AM products after manufacturing (such as hearing instruments).

Because a supply chain is comprised at the highest level of two root processes: 1) the production planning and inventory control process, and 2) the distribution and logistics process (Beamon, 1998), it differs from traditional manufacturing processes at the root process level of production planning and inventory control. Additive manufacturing needs much more design work than traditional manufacturing due the complexity of AM technology. On the other hand, AM has the potential to reduce or even entirely remove post-production warehousing processes. Additive manufacturing also needs one extra step in the raw material manufacturing phase as well as in the post-production and quality assurance phases.

Roles of the different firms in the AM supply chain processes

The interviewees were asked to describe (and offer secondary data on) what kinds of activities their firms are involved in with regard to AM generally and the AM supply chain specifically. The roles of the studied firms in the supply chain process were mapped and are summarized in Table 4. This map reveals that every process phase of the AM supply chain is covered through the firms involved in this study. All but two (B and J) of the firms are currently working with AM, and their positions in the AM supply chain process are marked with x. The two firms not yet involved in an AM supply chain clearly indicated where they would be positioned in AM processes, and these are marked as o. At this point, distribution and logistics are excluded from the analysis because all of the firms is taking part have outsourced them to external logistics firms.

Table 4. Roles of interview target firms in the AM supply chain process

Firm type	Firm	AM raw material manufacturing	Product design	Design for AM	AM production	Post-processing	Quality assurance
1: Large manufacturing brand owner firms	R		x				
	U	x	x	x	x	x	x
	S		x			x	x
	T		x	x	x	x	x
2: Medium-sized manufacturing brand owner firms	A		x				
	H		x				
	I		x			x	
	K		x				
	M		x				
3: Small or medium sized OEMs and ODMs	B					o	
	E					x	
	F		x			x	
	J					o	
4: AM service and machine operators	N			x	x		x
	Q			x	x		
5: Engineering and industrial design	C		x				
	D		x	x			
	G		x				
	L		x				
	P		x	x			
x = current role in the AM supply chain process o = expected/planned role in the AM supply chain process, not yet implemented							

Table 4 shows that large product brand owners (type 1), small and medium OEMs/ODMs (type 3), and AM machine operators (type 4) have distinct supply chain process roles based on their activities, whereas medium-sized brand owners and industrial designers show some similarities. Two of the four large firms (U and T) are active almost throughout the AM supply chain process, and they have implemented their own AM machines for in-house applications. The other large firm (U) also produces AM-specific metallic powder for internal use and external sales. In the smaller firms, AM machines are implemented by only two AM service providers, which have also invested in knowledge of AM design. As machine operators, this was seen as crucial by the interviewees from these two firms. Two of the four OEMs/ODMs that operate mainly with traditional manufacturing technology are actively taking part in the post-processing of AM components, meaning that they had to develop their capabilities for very accurate machining operations to almost net-shaped parts (close to the dimension of the ready-to-be-used parts). Otherwise, the majority of the firms concentrate on their own product design and on assembling the products, but many of the AM phases have been outsourced to smaller firms specializing in AM.

Required supply chain innovations and activities to leverage AM

In order to leverage AM in their firms, interviewees expected that various innovations were required, and these are presented in Table 5. The most frequently expressed needs deal with new practices in product development, investments in digital systems in the supply chain, and a partnership approach in the supply chain, expressed by over half of the respondents. Each of the other topics was discussed by fewer respondents.

Requirements for supply chain innovations during AM adoption depend on the strategies of certain leader firms that decide to invest in either machinery or AM manufactured goods. The interview data suggest that it is not clear who should own the AM machines. Currently, two large firms have implemented their own AM machines, but these are solely for internal use. Two service providers are the only smaller firms that had implemented industrial-scale AM so their capacity would be accessible to others as well, but they will need a strong and co-operative supply chain for AM to become competitive. The interviewees anticipated that new firms may be emerging in AM-oriented supply chains. Also, possibilities for other firms to implement AM machines may open up as the technology improves.

Based on the interviews, *supply chain business process innovations* deal with product development, order fulfillment, demand management, customer/supplier relationship management, and service capacity.

Innovations in product development processes are expected because of the faster iteration cycles with real components instead of mock-ups or weak quality prototypes. The capacity fill rate of the building platform plays a crucial role in terms of costs. Optimizing the fill rate is, therefore, a goal for firms that have implemented AM, and it will require innovation activities in order fulfillment, demand management, and service capacity. In current practice, one AM machine operates with only one material, since material changes are currently very expensive due to the required cleaning process of the machine. Therefore, interviewees suggested that at least in the beginning there should be a handful of machines with different material set-ups that firms could load with different materials, and an agreed-upon way to share the production resources.

Supply chain technology innovations were expected in terms of investing in digital systems that promote digitalization in the entire design-to-manufacturing chain and changes in manufacturing methods and open up the possibility to effectively streamline the design-to-manufacturing chain and enhance transparency. The change in manufacturing methods means that with AM technology, supply chain management has new tools to make manufacturing processes more flexible. One important question to solve is how to integrate AM in the supply chain of a product that consists mostly of traditionally manufactured components with only a few AM components.

Supply chain structure innovations and, more precisely, innovations with suppliers and customers, deal with models of cooperation, specialization, and co-location of expertise; the emergence of new actors and job profiles; and alternative initiators of innovations. According to the interviews, a suitable operations model in the supply chain structure is cooperation, which requires finding the right partnerships. Additive manufacturing technology is new and complex, and cooperation between the customer and the supplier is needed to maximize R&D innovations. Some interviewees thought specialization would be the best operating model for cooperation, whereas others indicated that expertise centers should be formed for AM. Expertise centers were described as multiple specialized firms within the same building—or at least in very close proximity—where partnership is close and several firms can work as one firm. An interviewee in one of the AM service provider firms revealed that they have already started to implement this kind of model by acquiring premises large enough for multiple firms and negotiating with promising partner firms. More actors and new job descriptions are expected to emerge in the supply chains in each scenario. New actors could emerge in the field of total AM supply chain management that would optimize all steps in the value chain and handle quality assurance. According to one interviewee, this would be the best way of managing expertise centers.

Regarding who should be the leader of AM implementation and network innovators, one interviewee in a medium-sized OEM firm said they would like to source AM parts or services traditionally from the subcontractor with the lowest bid. Interviewees in other OEMs saw collaboration or cooperation as a better model, although they mentioned that they would expect their subcontractors to be the initiators in providing new technology capacity to them. Subcontractors, on the other hand, are waiting for their customers to ask them to provide AM capabilities or, ideally, to start to co-develop AM with them. Two of the large firms that had implemented their own AM machines had also defined AM as an important new technology in their strategy. Their interviewees stated that the implementation of AM began when they discovered some of their important components were easier or faster to manufacture with AM. Now their strategic aim is to educate their designers so AM will not only be a special manufacturing method for special parts but could also be used for more general purposes. This is expected to be a wise way to generate product design innovations. Interviewees in two other large firms said their subcontractors implemented AM based on their requests, and then the required capabilities were co-developed. They also stated that intellectual property rights were the most important thing in selecting subcontractors for co-development.

Table 5. Expected innovation requirements in supply chains to leverage AM

Element of supply chain innovation	**Description: Domains where innovation activities are expected**	**Specific innovation example**	**Example quotations**	**The number of the firms (within the five firm types) where innovation was expected**				
				1	**2**	**3**	**4**	**5**
Innovations in supply chain business processes	Product development	Possibility to manufacture working prototype components for testing a complex product or assembly	"Design schedules have become so short nowadays. After our designer has designed the component, it needs to be integrated into the product to be tested within three weeks. We don't have any other possibility but to have the components additively manufactured so that they are real working components, not just weak prototypes. (Firm U)	4	1		2	2
	Order fulfillment	A new real-time pricing system based on delivery times, with online quotations for customers	"We had to come up with a new pricing system with online quotations to ensure that our building platform is always filled to the acceptable rate and that the customers have fast delivery times if needed, because that is what we promise." (Firm Q)			1	2	

	Demand management	A new tool to estimate and forecast both the demand and manufacturing time	"Our main goal has been to maximize the machine utilization rate. We have gathered a lot of know-how to excel in forecasting the manufacturing schedule, to handle incoming orders by promising the right delivery times." (Firm N)				2	
	Customer/ supplier relationship management	A new tool for quality management and quality documentation requested by the customer, developed together with the customer, AM producer, and supplier	"We demanded that our AM supplier had to develop new systems to guarantee the quality of AM parts. Eventually we developed new systems for quality management with our supplier, and they took care of the documentation and access to all the material data from their feedstock supplier." (Firm U)	3	3		2	
	Service capacity	Overall innovation needed to create a new front-end supply chain business process for AM services to fulfill customers' expectations (delivery time, multiple batch sizes, quality assurance, and reasonable costs)	"Good service capacity is expected from our AM suppliers, meaning that we must know when we get the part, how the quality is assured, and how much it costs, since these differ from the traditional sourcing." (Firm A)	2	1			
Innovations in supply chain technology	Investments in digital systems in the entire design-to-manufacturing chain	Using the same digital model throughout different manufacturing phases and technologies making development and production more efficient and of better quality	"We have developed our systems so that our designers make the design model in a certain way and we have integrated systems to use the same model in each phase from R&D to product assembly. We can now use the same model in digital simulations, printing the part, post-processing it, and measuring the part to inspect the quality […]." (Firm U)	4	3	1		3
	Change in manufacturing methods creates opportunities for new tools for the supply chain and operations management	New supply chain and operations management tools to take advantage of AM benefits and integrate the AM technology to production, i.e. a tool to optimize cost, delivery time and forecast benefits of faster delivery	"Because of the tough competition, the design cycles and new product cycles are so short that it does not make economic sense to utilize the mass production method for small batches of certain components." (Firm U)	4		2	1	1
Supply chain structure: Innovation with suppliers/ customers	Partnership, cooperation	Open and cooperative relationships between the different companies in the supply chain, i.e. suppliers are expected to raise new ideas for production to the customer	"We definitely take up ideas from our subcontractors, and we constantly try to improve co-operation with our subcontractors. Cooperation with subcontractors is what makes us successful, and we can trust that our subcontractors also develop their competences to have the latest methodological expertise in AM." (Firm K)		4	2	2	4

	Specialization	Seeking and adding new companies to the supply chain and share production resources of the different firms	"None of our established suppliers have started to provide us the possibility of AM, so we had to seek those smaller companies specialized in AM. It seems that this is the case of how we need to operate. Of course there are many new methods in AM, so one company cannot handle them all." (Firm M)		1	1	2	2
	Expertise centers: clusters of specialized firms in the same or a close location	Innovative way of relocating companies near to each other for more efficient supply chain structure	"Although the digitalization level of firms is growing and AM operators can basically be anywhere in the world, post-processing is very important for the manufacturing industry. It requires a geographically relatively tight ecosystem to benefit, for example, from the relative speed of the AM method." (Firm N)			1	2	1
	New supply chain roles and job descriptions	A new role for design chain management that carries the original idea and requirements through different phases of design, manufacturing with different technologies, and quality management	"New professions are emerging as we speak. Part of it is formed from old quality assurance or material management, and in this whole manufacturing process there will be, for example, design management professions related to the design chain that have to carry the idea through to the end with certain criteria. And there's a lot of designer stuff to think about through different stages. Now we try to take care of those responsibilities, but it is complicated because we are just a small company and our customers are big companies." (Firm N)			1	1	2

We further analyzed participating firms' experiences concerning supply chain innovations to identify potential patterns of innovations according to firm type. Table 5 implies that different types of firms experience different kinds of innovation needs. Table 5 shows four distinctive clusters of participation, which provide evidence about the supply chain innovation within the specific context of a supply chain process phase.

First, product development process innovations are expected widely in different firms (firm types 1, 2, 4, and 5, that is, in all firm types except small/medium OEMs/ODMs). Product development innovations concern mostly the early parts of the supply chain, from material development to product design. Here, the collaboration between traditional product designers and designers with advanced AM design skills is crucial because in many cases traditional product designers do not know what is possible with AM and, on the other hand, AM designers do not have the product-specific knowledge to implement AM ideas.

Second, AM service providers (firm type 4) are experiencing innovations throughout supply chain business processes. These innovations mainly include the latter part of the supply chain, from manufacturing to delivery. This pattern may stem from the emerging nature of business and business models for AM service provision.

Third, innovations in supply chain technologies are expected evenly throughout the supply chain positions. Supply chain technology innovations are linked with process and structure innovations, as they can be seen to support each other. Product development innovations will benefit from the increased accuracy of digital designs. Order fulfillment and service capacity will benefit from the increased use of digital systems and new operations management tools.

Fourth, interviewees in the smaller firms (and in medium firms to some degree) particularly emphasized supply chain structure innovations, while large firms did not. This pattern may reflect the advantage that large firms have in term of capabilities and possibilities to invest in the whole AM supply chain process. Small and medium firms are restricted in terms of their capital and capabilities, which leads to the need for partnerships or cooperation with firms as complementary capability sources.

Discussion

This paper inspected AM in industrial goods manufacturing and its inter-organizational supply chains holistically, and supply chain innovations when firms are implementing AM into their processes. This innovation process should not be seen as only a linear process where one aspect of AM has a direct effect on the supply chain, creating opportunities for supply chain innovations. Innovation can also happen the other way around, where supply chain innovations have an effect on the adoption, implementation, or utilization of AM.

The first research question inquired: *What kinds of contextual changes take place in business-to-business AM supply chains?* While earlier empirical research on AM supply chains has primarily taken a consumer goods-centric, intra-organizational, and single-firm perspective (e.g., Oettmeier and Hoffmann, 2016; Rogers *et al*., 2016; Rylands *et al*., 2016), this study covered the AM supply chain broadly, particularly in machine manufacturing and process industries. Five major contextual changes were identified, as reported in Table 3. The general finding that AM complements rather than replaces traditional manufacturing lends support to Rylands *et al*.'s (2016) ideas. As a contrast to previous research that portrays AM as a means to simplify the supply chain and improve its efficiency (e.g., Holmström *et al.*, 2010), our findings highlight the complexity of the supply chain transformation associated with AM, drawing attention to the new kinds of firms (i.e., partners), material flows, and digital information flows within the supply chain.

The most frequently expressed change concerned the digitalization of the entire design-to-manufacturing chain, which links directly with the firms involved and with changes in the material flow, and also confirms the centrality of the digital transformation pointed out in earlier AM-related research (Campbell *et al*., 2011). However, this digitalization trend and its implications have not been analyzed sufficiently in previous supply chain research or in AM specifically. Although digitalization is not solely an AM-specific change, AM and other digital manufacturing technologies are driving industries in a more digitalized direction. On the other hand, fully leveraging digital manufacturing technologies will require adopting a holistic view of the digitalized supply chain. This may have far wider effects than just for manufacturing processes. For example, product designers with different roles in the supply chain can benefit from the possibility of co-designing products in real time using suitable design software. Digitalization also has the possibility to enhance the response time in customer relationships.

The second research question asked: *How—through what types of activities—do different firms participate in the AM supply chain process?* Its response required mapping the AM supply chain process (Figure 1) and different firms' involvement in it (Table 4). The findings revealed that different types of firms have different roles across the supply chain process. The findings contribute to research that acknowledges the supply chain implications of AM (Rogers *et al*., 2016; Rylands *et al*., 2016; Thomas, 2016; Oettmeier and Hofmann, 2016) by showing evidence that AM is not an isolated innovation within one firm and gaining its benefits requires and enables the involvement of different types of firms in the supply chain. In particular, SMEs with traditional manufacturing equipment are actively seeking to be part of the AM supply chain in the post-processing phase, which reflects Strong *et al*.'s (2018) prediction that post-producing is a way for machinery SMEs to join the AM supply chain.

The description of the AM supply chain process includes the phases and activities needed in the AM supply chain context of this study (goods manufacturing, metallic AM) and provides a starting point for studies in other fields. Respective supply chains in different contexts may need some additional phases.

For the third research question—*How can firms leverage AM through innovations in their supply chains?*—the interviewees' experiences of required AM supply chain innovations were mapped. We identified a total of 11 required innovation expectations (Table 5) that were divided into 3 categories, based on the framework of Arlbjørn *et al*. (2011). The findings suggest that manufacturing technology innovations such as AM cannot be seen as isolated innovations that could be leveraged merely as a technology adoption task. Instead, they need to be viewed as a systemic innovation requiring complementary innovations to realize their benefits at full scale (Chesbrough and Teece, 2002; Martinsuo and Luomaranta, 2018). Martinsuo and Luomaranta (2018) raised the question about what kinds of innovations could be complementary for AM adoption stemming from the systemic innovation nature of AM, and Thomas (2016) asked how the whole supply chain would benefit from AM. This study provides evidence that supply chain innovations complement AM technology and, thereby, support the technology's adoption. Supply chain innovations are also a means for the entire supply chain to benefit from AM and to help firms leverage AM effectively.

Based on a further analysis, four different patterns were identified concerning the depth and focus of the firms' perceived innovation requirements for leveraging AM. The broad expectation across the supply chain regarding the possibility of enhanced product development is consistent with a previous study that pointed out the need to develop product design activities to promote AM adoption (Martinsuo and Luomaranta, 2018). Another broad requirement spanning the supply chain addresses the need to invest in digital systems and supply chain operations management tools, which Campbell *et al.* (2011) predicted. The digitalization of production and supply chains affects entire industries, not just single firms. Additive manufacturing service providers' specific expectations regarding innovations in business processes reflect the emergent phase of AM service business models, thereby lending support to findings in Rogers *et al.* (2016).

Implementing an AM machine and processes is demanding both financially and operationally. It requires new expertise within a firm, as well as supply chain innovations that emphasize cooperation, coordination, and specialization. A collaborative approach has been emphasized in this study as a means to benefit from AM-driven changes, especially in the SME context, confirming Oettmeier and Hofmann's (2017) predictions. A consortium of smaller firms co-locating, forming expertise centers, and having a strong network with each other could promote the increased speed through AM production. This finding is in contrast with Sasson and Johnson (2016), who predicted that large firms would evolve into AM supercenters. While larger firms may indeed evolve according to this prediction in the future, SMEs in particular require complementary capabilities from their broader networks. The perspective of an entire supply chain in AM-related innovations reveals that firms in different supply chain positions will have different ways to support AM adoption and leverage the novel technology in their networks.

The thematic framework of Arlbjørn *et al.* (2011) was used in the analysis to map supply chain innovations, and it was found useful for AM supply chains. However, the interviewees often linked their needs and the implementation of supply chain innovations to changes in the AM supply chain and the broader business environment. Also, the business-to-business context appeared as more complex in its supply chain operations than ordinary consumer goods manufacturing. Changes in the supply chain context and the business environment generally can, therefore, be seen as key factors in supply chain innovations. Therefore, the results of this exploratory study offer evidence to elaborate the framework of Arlbjørn *et al*. (2011) by adding the context of supply chain innovations as a new analytical dimension. This could enhance the further usefulness of the framework by providing a broader contextual view of supply chain innovations, which has already been recognized as important by Ojha *et al.* (2016).

Conclusion

Contributions

Since AM technologies are being considered in various industries, firms need information about how they can promote and speed up AM adoption and succeed with the new technologies. The results of this study provide a process model of the AM supply chain, offering evidence of the activities and firms involved in producing goods through metallic AM. The specific involvement of different types of firms in the AM supply chain process was described, indicating that AM adoption takes place very differently for different supply chain firms. Since AM machines are purchased and implemented only by certain firms, the implications of AM implementation are spread throughout the supply chain and require an understanding of multiple perspectives to become effective for all supply chain firms.

Firms experience various practical changes in their supply chains when considering and implementing AM. These changes can also be drivers for AM, for example, the digitalization of the whole design-to-manufacturing chain. Successful AM adoption requires complementary supply chain innovations in business processes, technology, and structure. They also need awareness and sensitivity to the specific context in which AM supply chain innovations are implemented, and we have proposed adding the innovation context to the framework of supply chain innovations.

The findings provided evidence on using the framework of supply chain innovations to acquire a holistic view of the possible effects of AM and revealed the effects of AM on supply chains and inter-organizational relationships. Supply chain innovations can complement AM technology innovations during AM adoption and offer practical mechanisms for the entire supply chain to benefit from AM, which can help firms leverage AM more effectively.

Practical implications

Engaging the supply chain more broadly in AM-related discussions will help the different firms justify their investment decisions, negotiate their network position, and access other firms as sources of complementary capabilities. The results serve as an inspiration for practitioners to view the implementation and leveraging of AM from a wider perspective through the framework of supply chain innovations. Practitioners can use the ideas to map the relevant changes stemming from AM, generate supply chain innovations, improve their supply chains, and, consequently, enhance AM adoption.

Different companies in the supply chain have specific expectations of AM. Some expectations, such as those concerning a certain service capacity, can be solved by creating a new front-end supply chain business process for AM services that would inform customers and other partners about the implications and requirements of AM (e.g., delivery time, quality assurance, cost). Furthermore, because the implementation of AM may influence the strategic location of manufacturing facilities and capability needs in a society, the results are useful for designing new training programs for SMEs or within larger firms, and when funding institutions screen the business plans of newly founded AM firms.

Limitations and avenues for further research

The exploratory research design enabled a broad exploration of the phenomenon but not in-depth observations or analysis of a specific case. All firms were from the machine and process industry, and the AM technology was metallic AM, which limits the findings to this context. In some firms, only one person was interviewed and additional documentation or website data were not available for triangulation purposes, which may limit the reliability of the data. However, efforts were made to identify knowledgeable key informants, use secondary data where possible, and test the main results in collaborative workshops to confirm the key findings. Not all relevant supply chain innovations were covered in this study, and further research is needed to delve deeper into other AM-related innovation scenarios in the future. Furthermore, the firms did not necessarily represent the same supply chains, so conclusions concerning a single supply chain cannot be made.

In the future, a single supply chain and its AM investment should be investigated to confirm this study's predictions and develop them further. Since cooperation between firms was considered important in this study, it would be beneficial to study to what degree large firms' support of their respective supply chains explains the successful adoption of AM throughout the supply chain.

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PUBLICATION III

Additive manufacturing innovations: Stakeholders' influence in enhancing sustainability and responsibility

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Additive manufacturing innovations: Stakeholders' influence in enhancing sustainability and responsibility

Toni Luomaranta*

Tampere University, Industrial Engineering and Management,
Korkeakoulunkatu 7, 33720 Tampere, Finland.
E-mail: toni.luomaranta@tuni.fi
* Corresponding author

Abstract: Additive manufacturing (AM) is receiving increasing attention in the manufacturing industry as a collection of novel advanced production technologies, product innovations and innovative supply chains and processes. Companies implementing AM are active in innovation, but successful innovation requires support from other companies in the supply chain and from stakeholders outside of the supply chain. This exploratory study seeks to better understand the mechanism behind stakeholders' involvement in AM innovation activities. The focus is on how stakeholders' involvement enhances the success, sustainability and responsibility of AM innovations. The findings reveal who the stakeholders are and how they influence the innovation processes of companies utilising AM in their manufacturing processes. The study contributes to the field of innovation management in the context of AM by detailing the network complexity in AM innovations and guiding AM companies towards the stakeholders who can improve the success, sustainability and responsibility of AM innovations.

Keywords: additive manufacturing; stakeholder involvement; innovation; sustainable innovation, responsible innovation.

1 Introduction

Additive manufacturing (AM) is a relatively novel manufacturing approach that implies changes in production technologies, the use of digital product designs and a process of joining and adding material, usually layer by layer (ASTM, 2012), to produce innovative goods. The diffusion of AM technologies in the manufacturing industry will require innovations in the business models, supply chains and products and services of the companies involved (Martinsuo and Luomaranta, 2018; Luomaranta and Martinsuo, 2020). There is a growing need for more sustainable and responsible innovations, and AM can become one of the solutions for more sustainable manufacturing (Ford and Despeisse, 2016; Beltagui et al., 2020).

Innovation, in its classical sense, means the introduction of a new product, process or business model for a commercial purpose (Schumpeter, 1934). Creating and introducing new offerings requires a systematic innovation process (Drucker, 1985), and, besides companies operating in the direct AM supply chain, various stakeholders with different interests and demands influence AM innovations. These stakeholders tend to be important organisations that have the power to influence the innovation process to enhance the sustainability and responsibility of AM innovations (Berger et al., 2004; Pagell and Shevchenko, 2014). This study concentrates on innovations in AM, including both the manufacturing technologies and the new goods being manufactured, and on the stakeholders' influence on the sustainability and responsibility of AM innovations.

There are multiple definitions of stakeholders (Miles, 2017), and these different definitions focus on the relevant stakeholder attributes depending on the context of the analysis situation (Freeman et al., 2010). This study takes stakeholders to be external organisations that have an interest in or contribute to AM but are not key actors in the direct AM supply chain.

Earlier research has identified that research and training organisations have an important role in providing AM-related training and transferring knowledge to companies (Rylands et al., 2016). Standardisation organisations are important stakeholders when standards are created for emerging technologies (Monzón et al., 2015). Before the specific work of standardisation organisations, other stakeholders, such as trade organisations and engineering associations, specify the need for standards and influence the standardisation process (Koch, 2017). Previous research has identified and mentioned such AM stakeholders only briefly, and their input in AM innovations is poorly understood.

The purpose of this study is to explore stakeholders' involvement in the innovation process of AM. The goal is to understand how different stakeholders participate and use power in AM innovation activities in relation to companies in the AM supply chain whose aim is to create sustainable and responsible innovations or at least to try to minimise the negative effects of the AM innovations to meet the requirements of the stakeholders. This paper poses the following research question: "How do different stakeholders influence AM innovation activities in relation to companies in the AM supply chain to enhance the sustainability and responsibility of AM innovations?"

2 Literature review

Defining stakeholders

The term "stakeholders" is frequently used in management studies, which may be the reason why the term has many varying definitions. (Miles, 2017). From the viewpoint of stakeholder theory, stakeholders are assumed to be a part of business and are defined as "groups or individuals that have a stake in the success or failure of a business" (Freeman et al., 2010, p. xv). Often, the definitions of the stakeholders are formed in such a manner that the context and stakeholders' attributes serve the purpose of the study (Freeman et al., 2010), meaning that in the case of a big multinational company, the stakeholders could be the customers, suppliers and employees. In the strategic management literature, the focus is usually on the attempt to define which stakeholders are important from a company's perspective and to which stakeholders the managers should pay attention (Mitchell et al., 1997). In such cases, the stakeholders usually include shareholders, company employees, customers, suppliers and sometimes even competitors and are referred to as primary stakeholders; then, external stakeholders are the organisations external to the supply chain. External stakeholders are not directly involved in manufacturing and the supply chain but may indirectly influence or affect, for example, the innovation process (Freeman et al., 2010). Such external stakeholders can be, for example, national governmental organisations.

Some of the management frameworks treat companies' business environment changes as external forces (see, for example, the PESTLE analysis, Vlados and Chatzinikolaou, 2019), with legislation, for example, being seen as part of such forces. These external forces are things that companies cannot influence but which have an influence on the company. External forces could, however, quite often be categorised as external stakeholders. Stakeholder theory suggests that the relationship is more complex than one-way forces, to which companies need to adjust, and that while external stakeholders have an effect on a company's actions, companies can also use the relationship with external stakeholders as a two-way relationship (Freeman et al., 2010).

Scholars have noticed that companies are paying relatively little attention to systematically identifying and analysing important stakeholders (Bryson, 2004; Pagell and Shevchenko, 2014; Meixell and Luoma, 2015), which makes this study relevant for managers and practitioners. When studying the involvement of the stakeholders in a company's innovation process, defining the stakeholders too narrowly would most likely lead to ignoring important stakeholders from the perspective of innovation in an emerging technological area. Therefore, when it comes to stakeholders, this study looks beyond the traditional consumeristic management point of view and concentrates on external organisations – external stakeholders – that have an interest in or contribute to AM rather than to the companies, institutions or customers who are directly involved in the AM-product supply chain. An organisation can also have a shifting role between actively participating to the supply chain level processes in one occasion and acting as a stakeholder on other, depending on the specific innovation and the phase of the innovation process.

Stakeholder influence on the innovation processes to enhance sustainability and responsibility

Sustainable innovations and responsible innovations partially overlap in their scientific use, and there is a vivid discussion to clarify the definitions (see Owen and Pansera, 2019). According to common sense, sustainability is often associated with environmental aspects and with responsibility to social issues. One of the most cited sustainable development definitions (where innovation falls under the category of development) comes from the Brundtland Report: "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 8). Responsible innovation is defined as "taking care of the future through collective stewardship of science and innovation in the present" (Stilgoe et al., 2013, p. 1570). What is common in these definitions is the consideration of the social and environmental aspects, which can be easily neglected due to focus on short-sighted economic growth (Owen and Pansera, 2019). The notion of collective stewardship increases the need for research studying the innovation network and the stakeholders who have an influence on the sustainability and responsibility aspects of AM innovations.

When looking into the stakeholder involvement in the focal company's innovation process, researchers have noted that the relationships with stakeholders have been increasingly considered as an important way of developing innovations (Haeckel, 2004). One way for stakeholders to participate in the innovation process is to offer knowledge from the network that they represent. For example, the stakeholder could be an organisation representing different customers. Such stakeholders can offer access to a dense network or hub of organisations that are distinct from a company's focal supply chain as well as provide a different view of the marketplace and give early warnings about shifts in public tastes and values (Yaziji, 2004). An example from the biomedical innovations sector involved a firm whose collaborative relationships with partners in a hub enabled by a stakeholder were a key determinant of successful innovation (Powell et al., 1996). Developing relationships with such stakeholders can foster innovation by creating suitable conditions for relevant ideas.

Stakeholders may thus have a general influence on innovation success, but they may also be pursuing other goals. These goals may include enhancing the sustainability and responsibility of innovations. As Ottosson (2009) argues, the different sectors of our society each have their own role in innovation development: companies seek sustainable profits to their innovative products and services, the public sector seeks good and sustainable services for the people in the society, and the idealistic sector (NGOs, for example) aims for responsibility.

In addition to passive involvement, stakeholders can have a more active role in the innovation process. Findings from strategic management shows that organisations are more inclined to protect their existing processes than to develop new ones until they are sure that the development is almost risk free. Therefore, a stakeholder outside of the company can try to force the innovation if a company does not do it voluntarily (Van de Ven, 1986). It has even been argued that especially larger companies do not improve their sustainability (social and environmental) without stakeholder involvement (Pagell and Shevchenko, 2014). Without enough legislative pressure for the larger companies, smaller innovative companies are more likely to drive industrial manufacturing to emphasise responsibility (Shevchenko et al., 2016), but they lack the resources of larger companies, which decreases the chances of success (Minetola and Eyers, 2018). Developing relationships with non-governmental organisations (NGOs) can strengthen any company's social legitimacy. It can be argued that companies need these relationships with NGOs to be perceived as socially and environmentally responsible (Berger et al., 2004). Company-NGO partnerships can address both broad and complex societal issues, and such partnerships can be a source of competitive advantage (Bonfiglioli et al., 2006).

Combining the stakeholder theory and sustainable and responsible innovation make for an interesting research avenue that could identify legitimate stakeholders whose involvement is beneficial (Mitchell et al., 1997). Therefore, from the perspective of responsible and sustainable innovations, it can be argued that certain (often larger) companies need the stakeholder pressure to enhance the sustainability and responsibility of their innovations. On the other hand, certain companies (often smaller and innovative) with an internal emphasis on sustainability and responsibility need the help of stakeholders in order to succeed in their innovation efforts and market diffusion. Thus, this study investigates stakeholder involvement in terms of which stakeholders can foster the sustainability and responsibility aspects of AM innovations as well as which stakeholders can help in the success of sustainable and responsible innovations, answering directly to the need for future research argued by Pagell and Shevchenko (2014, p. 47): “Future research will have to explicitly recognize the claims of stakeholders without an economic stake in the chain, treat these claims as equally valid to economic claims, and start to focus on ways to deal with situations where synergies cannot be created.”.

In the previous studies on AM, stakeholder involvement in the innovation processes was mentioned only briefly. The empirical studies have noted that organised customer groups or associations representing their customers can apply pressure to the AM manufacturing companies already in the design phase of a new product to consider sustainability aspects (Beltagui et al., 2020). Research and training organisations have been found to have an important role in providing AM-related training and transferring knowledge to companies (Rylands et al., 2016) so that the latter could start the AM innovations in the first place. Research organisations can also be of help later in the innovation process – for example, in the testing and development phases. When it comes to emerging technology, standardisation organisations are important stakeholders for the creation of standards (Monzón et al., 2015). Before the specific work of standardisation organisations, other stakeholders, such as trade organisations and engineering associations, specify the need for standards and influence the standardisation process (Koch, 2017). By developing relationships directly with the standardisation organisations, or more likely through engineering associations, companies can influence standardisation – for example, to make sure that it enhances their changes to diffuse their innovations. The focus in these studies has been mainly on a single stakeholder or the general innovation success, and the holistic analysis of the stakeholders’ influence on sustainability and responsibility has so far been neglected in the technological area of AM.

3 Research design and method

Data collection

The research design is qualitative and exploratory in nature because of limited previous knowledge on stakeholder involvement in AM innovation activities. The study involved two major industries where AM has shown great potential: car manufacturing and medical implants and devices. Organisations A and F are involved solely in the medical implants and devices industry. Organisation B represents the car manufacturing industry, and the rest of the organisations are involved in the AM industry more extensively and are part of both the car and medical implants industries. The technological background information on the companies that participated in the workshops and survey is presented in Table 1.

Table 1 Background information on organisations that participated in the workshops and survey

Organisation	*Role in AM*	*Stakeholder role*
Organisation A	AM designer, AM producer	
Organisation B	AM designer, customer	
Organisation C	Software developer	
Organisation D	AM designer, AM producer	Research organisation
Organisation E	AM designer, AM producer	Research organisation
Organisation F		Engineering association, training organisation
Organisation G	AM machine manufacturer, AM feedstock provider	
Organisation H		Engineering association, training organisation, research organisation
Organisation I	AM feedstock provider	Research organisation
Organisation J		Non-governmental organisation, research organisation, training organisation
Organisation K		Research organisation, training organisation
Organisation L		Education organisation, training organisation, research organisation
Organisation M		Training organisation, research organisation

During the first workshop, the participants were instructed to map their dedicated supply chain and the actors in it, including all the organisations and institutions inside and outside the supply chain with whom they were developing innovations.

After the listing of the stakeholders, a survey was sent to the company representatives concerning the activities of the stakeholders engaged with the AM companies. The question of the survey was this: “Based on your experience, what inputs or requirements do the external stakeholders bring to the network of companies in the additive manufacturing supply chain?” At this point, the external stakeholders were divided into the following categories: funding and insurance companies; training organisations; regulators and patent authorities; trade associations and customer representing organisations; research organisations; and others. Respondents could offer an open-ended response regarding each identified stakeholder and add the stakeholders they considered as relevant.

Another workshop was organised with the same companies and a group of researchers to identify the stakeholders’ interactions and activity inputs and outputs with the companies in the AM network. In this second workshop, the participants were divided into industry-specific teams (car manufacturing and medical implants and devices) to draw up and organise a process map that included the previously identified stakeholders and their inputs and requirements. The data created during the workshop covered the stakeholders’ relationships with the companies in the AM supply chain, the requirements of the stakeholders, the benefits to AM companies from the relationships, and the phase of the innovation process in which the stakeholders were involved. Discussions during the workshop were documented using memos and flipcharts.

Analysis

The analysis concentrates first on identifying and defining the stakeholders (see Table 2) and then on mapping the stakeholders' involvement for the three AM innovation process phases (Table 3). Based on the answers about the stakeholders from workshop 1, Table 2 was formed by listing all the relevant stakeholders, removing the statements concerning primary stakeholders, and combining the repeated attributes of the stakeholders into logical descriptions.

Based on these data, a stakeholder matrix mapping analysis was carried out according to the three phases of the innovation process, namely idea generation, idea development and the diffusion of developed concepts (Hansen and Birkinshaw, 2007). One of the most common stakeholder mapping methods is to use a two-by-two matrix with key attributes on both axes. The attributes can include, for example, power and interest, importance and influence, salience and power or support and opposition (Bryson, 2004; Hoejmose et al., 2013). For this study, the power and interest matrix was chosen because it provides the most insight for studying the stakeholders' involvement in innovation.

The interest attribute reveals whether the stakeholder is pro-active in their involvement or passive. It is also important to understand the power that each stakeholder possesses because this enables understanding whether the stakeholder is empowering or controlling the innovation process. Also, the power may lie in the ability to affect innovation in the short term or to affect its success and acceptance in the long-term (Mathur et al., 2007). In addition, to analyse further the stakeholders' influence in enhancing sustainability and responsibility, three different mechanisms were applied. To enhance sustainability and responsibility, the first two mechanisms that stakeholders can use, according to Meixell and Luoma (2015), are to purposefully foster the sustainability and responsibility aspects by giving knowledge or set pressure to them (which might be interpreted as resisting unharmful innovations). The third mechanism used by this study is the stakeholders offering help for already sustainable and responsible enough innovation to become successful. In the analysis, these three mechanisms are referred to as "fosters," "sets pressure" and "innovation help."

Figure 1 illustrates the power/interest matrix and the sustainability and responsibility enhancement mechanisms identified in this study. The data from the survey and the second workshop were used to analyse each phase of the innovation process (idea generation, idea development and diffusion) based on this analytic framework. During the analysis, the interest of the stakeholder was considered to be high if an AM company respondent described a stakeholder's influence as follows: "they brought the idea," "they started the discussion" or "they were very active." Concerning the respondents who were in the stakeholder role themselves, the interest was considered to be high if they claimed to have an active role, for example "we had the idea and then we tried to find a company to collaborate with us." In the analysis of power, strong power was coded if the respondents stated that "we have to comply" or "it is very important to collaborate with them." Weak power was coded if the statements were like the following: "it was not necessary but beneficial to us" or "we collaborated voluntarily." Regarding the sustainability- and responsibility-enhancement mechanisms, innovation help was coded for the stakeholder if there was no specific mention of sustainability and responsibility requirements or knowledge transfer. The fostering mechanism was coded if there were statements such as "they gave new knowledge about new more sustainable materials" or “we participated in training that covered societal responsibility issues.” Sets pressure was coded if the stakeholder used their power to force the company to comply with sustainability and responsibility requirements or if the influence of the stakeholder was mentioned in a negative manner even if the respondent addressed the sustainability- and responsibility-related issues that were criticised.

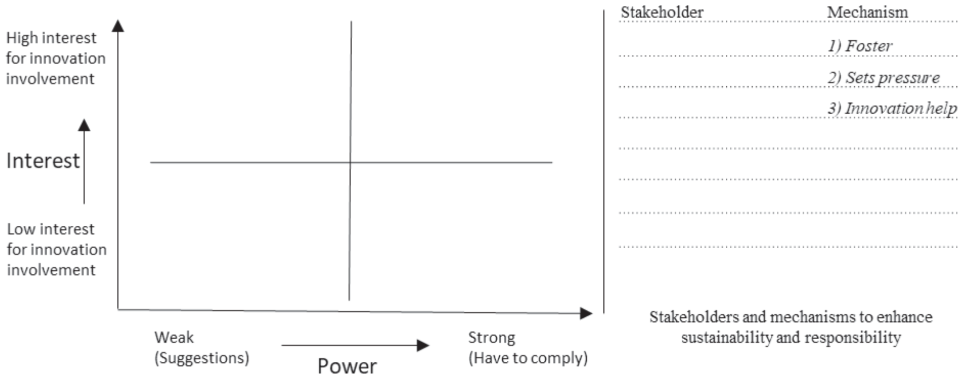


Figure 1 The analytic framework used to evaluate the stakeholders.

4 Findings

Identifying and describing the stakeholders

First, this study identified all the relevant key stakeholders for the AM innovation processes. They were the following: governmental organisations (regulators), NGOs, funding organisations, training organisations, research and technology organisations, standardisation organisations, patent organisations, trade associations, organisations representing customers and end-users and insurance companies. Figure 2 illustrates the research context – that is, the AM supply chain that is presented in the middle and the identified stakeholders. Any company within the manufacturing supply chain can be considered as a focal company, and the other companies are its primary stakeholders. The identified stakeholders are outside the supply chain.

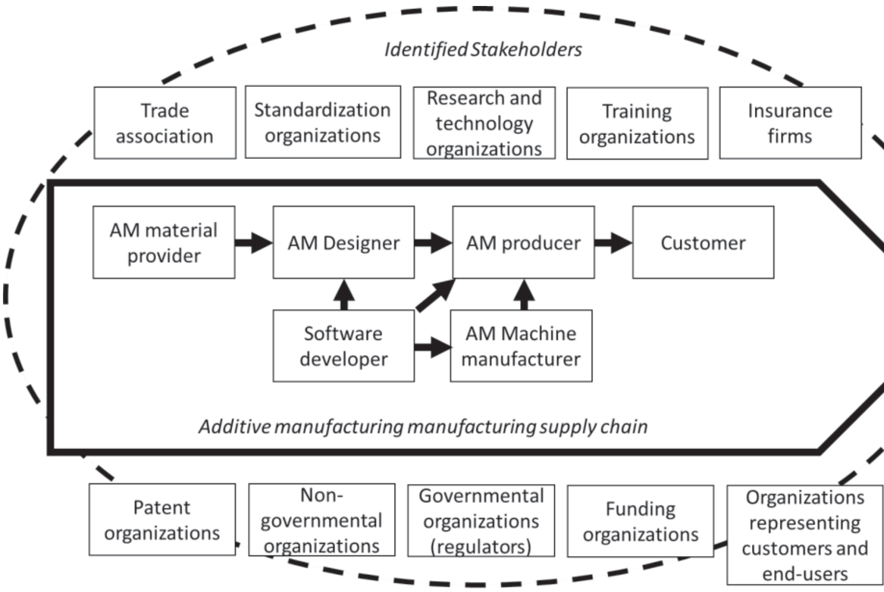


Figure 2 The AM supply chain and stakeholders.

Table 2 further defines the identified stakeholders based on the perspectives of the interviewed organisations. The descriptions are gathered from the answers to the survey and from the interviews. The descriptions reveal stakeholders' participation in and influence on the AM innovations – for example, via technology training and the emphasis of sustainable and responsible innovation or by giving an idea for a socially desirable innovation.

Table 2 Identified stakeholders and their descriptions

Stakeholder	*Description*
Governmental organisations (regulators)	Regulators generate laws and regulations. They also try to secure reliable and sound products for the societies they represent by providing descriptions of what companies should comply with and granting certificates. To create these certificates, laws and regulations, there needs to be collaboration at least with the research and technology organisations, AM machine manufacturers and AM producers. Regulators also set regulations or encourage companies to develop clean and material- and energy-saving technologies, and they set safety regulations and try to create new job opportunities for the society.
Non-governmental organisations (NGOs)	Non-governmental organisations in the context of AM are usually protective of the environment and/or the society. Damage to the environment may seem like a small issue at present, but as time goes on, repairing such damage becomes increasingly costly. Therefore, the information that NGOs can provide about the effects of new technology on the environment and society can be used to enhance the responsibility of the industry and to protect end-users and the wider society from the social consequences of the AM applications.
Funding organisations	Funding organisations can be national or, for example, European-level organisations. Their input, such as funding, enables new product development at quicker pace. They require that the companies provide comprehensive resource allocation and reporting to support the AM innovations in the most efficient way

	by multiplying the effect of funding to develop the innovation systems. Comprehensive reporting means that the sustainability and responsibility aspects of the innovations can be demanded and the implementation can be monitored. Funding can be terminated if the requirements are not met.
Training organisations	Training organisations provide standardised training, provide knowledge as quickly as possible to the organisation in the AM industry and offer different formats of training (e.g. academic, lifelong learning), and they can be universities or commercial organisations. Co-creating a vast knowledge base with research and technology organisations is necessary to achieve state-of-the-art knowledge, that can be used in training of new skills and best-practises. Also, training organisations need to gather funding, analyse the AM market and analyse the training purchasers' current situation. Training with multiple attendees can enhance the connection among different organisations and companies. The sustainable and responsible innovations aspects are embedded into the training. Education is included in this definition because education organisations have similar attributes for the innovations but at a larger scope.
Research and technology organisations	Research and technology organisations include universities, publicly funded organisations and privately funded institutes. Research and technology organisations are, in many cases, the main contributors/starting points for developing innovations in the early phases (idea generation, development), but they need companies to commercialise the innovations (development, diffusion). Research and technology organisations rely on funding organisations and company partners to fund their research and to advance innovations. Research and technology organisations contribute to new regulation–creating processes and to the new standard–making processes. They also transfer knowledge to training organisations. The sustainability and responsibility aspects of innovations are often embedded in the new innovation ideas (as publicly funded research and technology organisations mainly seek socially desirable innovations), and responsibility is also required by the funding organisations.
Standardisation organisations	Standardisation organisations coordinate expert groups to set the standards for the characteristics of AM-produced parts. This includes data formats, reliability, quality requirements and restrictions on software use. Standard compliance can be used to foster some technologies more than others. Standards try to secure the sustainability of different AM technologies and thus enhance responsible innovation activities. To create standards, standardisation organisations need to collaborate with industry experts, research and technology organisations and companies in the AM supply chain. Standards ensure a common understanding among different partners in the supply chain. This is important for communication and innovation purposes.
Patent organisations	Without patents innovations could be freely adopted by any competing company. Since there is a cost associated with innovation, patens serve as a security mechanism to protect the ownership of the innovation so that the owner could make a profit to cover the costs of the innovation. Patent organisations provide help and instructions to the companies seeking to file a patent application. Patents can also serve as a source of knowledge after they expire. Patents become public after a certain period, especially if the patented technology becomes an industry standard. After the patent expires or is licensed by the owner of the patent, companies can access the technology restricted by the patent.
Trade associations	Trade associations provide its members with new knowledge, strengthen the current networks and create and explore new networks. Trade organisations seek to gather information about the markets to provide marketing possibilities to different countries. Trade associations need to collaborate with research institutes and regulators, both within their country and outside, as well as with their member organisations. Professional associations, such as engineering associations, are included in this category of stakeholders.

Organisations representing customers and end-users	Organisations representing customers and end users identify possible applications and thematic areas for AM. They collect the requirements of the customers and the needs of end-user to analyse possibilities for further applications of AM. They have the possibility to influence the market (and, therefore, the whole supply chain) through the feedback of customers and end users. To influence the market, they need to collaborate with communities of interest, informal networks, educators and technology users. Companies in the AM value chain can use the knowledge from organisations representing customers and end users to better understand the potential needs and concerns of customers and end users.
Insurance companies	Especially in the medical sector, insurance companies can foster some technologies more than others through insurance decisions. This is an economic aspect of medical sector, which works as risk management (granting insurance for AM implants vs traditional implants), but insurance companies must follow regulations as well.

Analysing the stakeholders' involvement in the innovation process

The power/interest matrix analysis, together with the sustainability- and responsibility-enhancement analysis, was applied to each phase of the innovation process, respectively, and the results are presented in the Figures 3, 4 and 5. Figure 3 represents the early phase of the innovation process, where the idea for the innovation is generated.

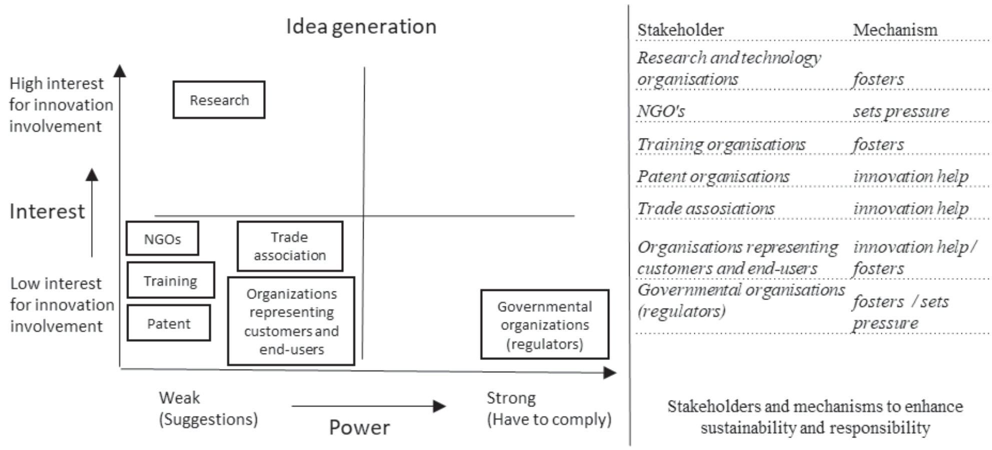


Figure 3 Stakeholder involvement (power/interest) in the idea-generation phase of additive manufacturing innovations, and mechanisms to enhance sustainability and responsibility.

For example, research and technology organisations were considered to be highly involved in the innovation process phases of the idea generation and idea development, as workshop participants discussed this actively. In the car manufacturing sector, research organisations were mentioned as the stakeholders who most often generate and introduce new AM component ideas or AM methods to the car manufacturers' products or production process. Especially regarding the medical implant innovations, it was mentioned that in the development phase, when the implants go through clinical testing, the research institutes are highly interested in being involved in the innovation process, but ultimately they do not have enough power to go through the whole innovation process by themselves and, therefore, need the company. On the other hand, the focal company does not necessarily need the research institute, but they can benefit from faster development with the involvement of the research institute. Research and technology organisation also often consider the sustainability and responsibility issues extensively, and this knowledge is passed on to the other organisations engaged in the innovation process.

Training organisations are an example of low interest and weak power in the first phase of the innovation process. Innovating companies need the education offered by the training organisations, but the training organisations have weak power to become involved in the innovation process. Of course, training organisations try to market their services, but the respondents saw their interest as lower than that of the research organisations. This was considered to be applicable in both the medical implant and the car manufacturing sector.

In the second phase of the innovation process, the idea is developed further into a viable solution ready to be diffused once this phase is finished. The analysis of stakeholder influence in the second phase of innovation process is presented in Figure 4. The respondents highlighted that, at this point, external funding is often sought from national or European-level funding organisations. If the funding is granted, this means strict reporting policies are required, and societal responsibility issues, such as public dissemination of the created knowledge or a high-enough gender balance of the personnel in the innovation process, are often included within the requirements.

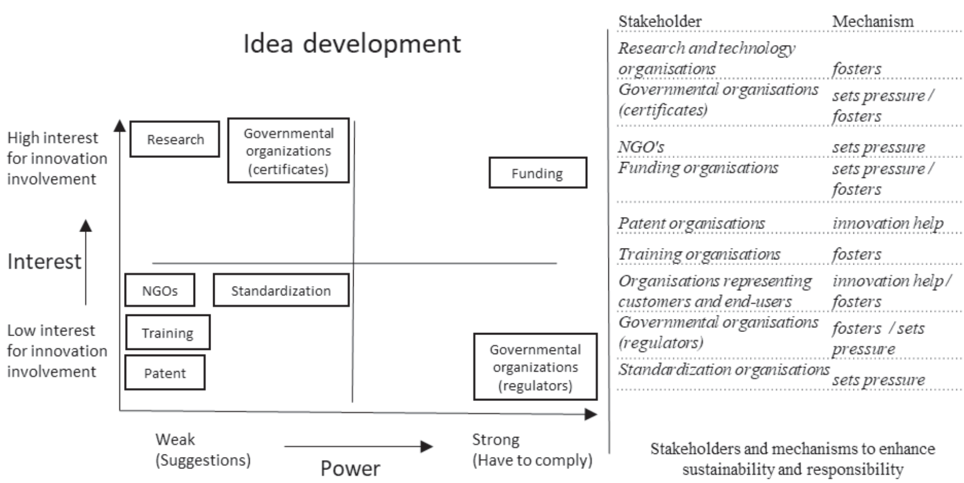
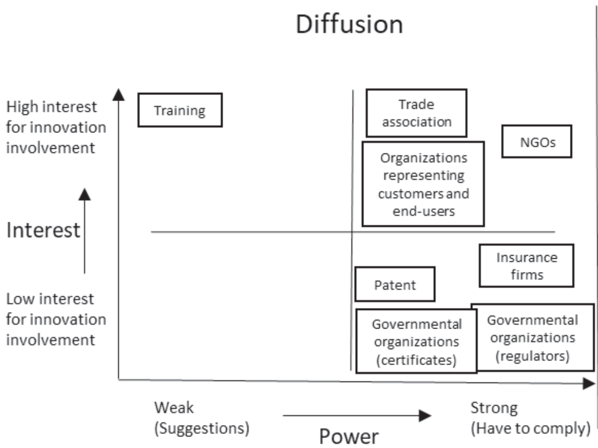


Figure 4 Stakeholder involvement (power/interest) in the idea-development phase of additive manufacturing innovations, and mechanisms to enhance sustainability and responsibility.

In the case of standardising emerging AM technology organisations are involved in order to create the best new standards for the technology. New AM technological solutions and new AM products must also have the relevant certificates to be diffused in the market. For this reason, the governmental organisations which oversee the certificates need to stay up to date by seeking new knowledge about the emerging technologies. The companies at the forefront can benefit from the participation of such organisations by getting their knowledge heard and getting feedback from both the standards and certifications to develop their products accordingly.

The analysis of the diffusion phase of the innovation process is presented in Figure 5. During the diffusion phase, organisations representing customers and end-users have a powerful position, and they are highly interested in being involved in the innovation process. These organisations are advocacy groups that can represent, for example, customers in a certain medical field or, in the car sector, conduct testing and inform the customers about the new innovations and their reliability. According to the workshop participants, such organisations try to provide the best new innovations to the customers they represent. Therefore, their role is important for AM companies trying to diffuse their innovations, meaning that AM companies try to convince and involve organisations representing customers to make sure that innovations are successfully diffused by being socially desirable.



Stakeholder	Mechanism
Training organisations	*fosters*
Governmental organisations (certificates)	*sets pressure / fosters*
NGO's	*sets pressure*
Insurance companies	*sets pressure / innovation help*
Patent organisations	*innovation help*
Trade assosiations	*innovation help*
Organisations representing customers and end-users	*innovation help / fosters*
Governmental organisations (regulators)	*fosters / sets pressure*

Stakeholders and mechanisms to enhance sustainability and responsibility

Figure 5 Stakeholder involvement (power/interest) in the diffusion phase of additive manufacturing innovations, and mechanisms to enhance sustainability and responsibility.

Compared to the research institutes, insurance companies are an example of the other end of the spectrum. Based on the answers to the survey and the data from the workshops, it was found that, in the context of this study, insurance companies do not seek to become involved to the innovation process actively; their involvement was only seen in the last phase of the innovation process, during innovation diffusion. Especially in the case of AM medical implants, the innovating companies have to convince the insurance companies that their product, which might be more expensive than traditional implants, are better for patients in the long run. Therefore, insurance companies were considered to have low interest in seeking to become involved in the innovation process, but they wield great power when it comes to successfully diffusing an innovation, such as a medical implant, in the market. This can, of course, be the case because of the rather novel nature of the AM sector and AM implants, and in the future the role of insurance companies can become more active. The insurance companies were not considered to be very important for the car manufacturing sector.

Discussion and conclusion

This paper started with the premise that AM innovations require the involvement of stakeholders both within and outside the direct supply chains of AM firms for the success of sustainability- and responsibility-oriented innovations. The research question was this: "How do different stakeholders influence AM innovation activities in relation to companies in the AM supply chain to enhance the sustainability and responsibility of AM innovations?" To be answer this question, the stakeholders were first identified and described. Then, their involvement was analysed using stakeholder analysis method of a two-by-two matrix, with interest in taking part in the innovation process as one attribute and the power to influence the company's decisions in the process as the other attribute. In addition, the mechanisms of stakeholder influence to enhance sustainability and responsibility was analysed using three categories: fostering, setting pressure or providing innovation help. This analysis was then conducted three times, once for each of the three innovation process phases – idea generation, development and diffusion – thus combining the method of stakeholder mapping (Bryson, 2004) and influence mechanisms (Meixell and Luoma, 2015) with the framework of the three phases of innovation process (Hansen and Birkinshaw, 2007).

The findings contribute to the limited previous research by adding the perspective of external stakeholders' influence to the AM innovation process to enhance sustainability and responsibility. This study offers new insights on the complex innovation networks in which different stakeholders take part. In these networks, the stakeholders use their power to influence the different companies in the AM supply chain or companies may seek the help of the stakeholders in order to enhance sustainability and responsibility outcomes. The findings contribute to the research need to recognize those stakeholders without an economic stake in the supply chain who can contribute to the sustainability and responsibility of innovations, as requested by Pagell and Shevchenko (2014). If a company's aim is to create possibly harmful innovations from the viewpoint of sustainability and responsibility, the results of this study offer no help, although such companies have to comply when a stakeholder with high power applies pressure.

This study reveals that different stakeholders support the sustainable and responsible AM innovation projects in four different ways: 1) reactively, when AM companies seek external support and stakeholder's power is weak, meaning that their advices or involvement is voluntary from the perspective of the innovating company; 2) stakeholder involvement can be very active but weak in power, meant to help the innovation success or to foster its sustainability or responsibility aspects; 3) the participation of stakeholders can be very active and powerful, meaning that companies need to comply with everything that the stakeholder advises (in this case, lack of compliance would usually greatly endanger the success of the innovations); and 4) the involvement interest of the stakeholder is low but powerful, and it sets sustainability- and responsibility-related pressure (for example, it would be against the laws and regulations to not comply).

Even though the earlier studies about the stakeholder involvement in AM product innovation processes were limited, it can be argued that the findings of this study are in line with the results by Rylands et al. (2016), namely that training organisations and research institutes are important for the AM innovation process. This study adds to this insight by noting that training can be a good way to educate AM companies in the areas of sustainability and responsibility. This study supports the study by Monzón et al. (2015), which claims that standardisation organisations also influence and can be influenced during the AM innovation process, and by Koch (2017), whose results indicate that engineering associations are important hubs of knowledge and ideas. The findings of this study also support the views of the stakeholder theory (Freeman et al., 2010), namely that innovations are not invented by a single company but that there are other stakeholders, especially external stakeholders, which have influence on the innovation process.

The findings offer practical contributions to managerial decisions by showing external stakeholders' influence in the AM innovation process to enhance sustainability and responsibility. The findings and the analytic framework provide AM companies with a way to identify the central stakeholders, promote the market access of socially desirable products and achieve other benefits during the innovation process. The study creates new knowledge from the perspective of the firms directly involved in the supply chain of AM, acknowledging the complex business network around them. This study provide insight to the companies who want to add sustainability and responsibility aspects to their innovations, by encouraging them to seek cooperation with stakeholders as one possible solution for the concern raised by Beltagui et al. (2020), namely how to increase the innovation success of smaller innovative companies.

This study used an exploratory research design with workshops and a qualitative survey to collect data. Using this kind of research design allowed to achieve a wide understanding of the phenomenon. However, the design does not allow to analyse single stakeholders very deeply. The empirical findings are limited to the medical and car business sectors of the AM industry, albeit the analysis framework might be well transferable to other research context. Each of the respondents also gave their organisation's point of view on the research task, possibly causing a single-respondent bias. In the future, more respondents from each organisation could be involved for a more in-depth study on external stakeholders' involvement. Also, respondents from the relevant stakeholders could be included to compare their intended ways to enhance sustainability and responsibility and the perceived mechanisms by the innovative companies.

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PUBLICATION IV

Additive manufacturing value chain adoption

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Additive manufacturing value chain adoption

Toni Luomaranta and Miia Martinsuo
Unit of Industrial Engineering and Management, Tampere University, Tampere, Finland

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Abstract

Purpose – Adopting additive manufacturing (AM) on a large-scale requires an adoption in company value chains. This may happen through product innovation and require interorganizational cooperation, but the value-adding potential of cooperation and application recognition is still poorly understood. This study aims to investigate the progress of AM adoption in innovation projects featuring AM application recognition and interorganizational cooperation in the value chain.

Design/methodology/approach – A multiple-case study was implemented in successful metallic AM adoption examples to increase the understanding of AM adoption in value chains. Primary data were collected through interviews and documents in three AM projects, and the data were analyzed qualitatively.

Findings – All three AM projects showed evidence of successful AM value chain adoption. Identifying the right application and the added value of AM within it were crucial starting points for finding new value chains. Interorganizational collaboration facilitated both value-based designs and experimentation with new supply chains. Thereby, the focal manufacturing company did not need to invest in AM machines. The key activities of the new value chain actors are mapped in the process of AM adoption.

Research limitations/implications – The cases are set in a business-to-business context, which narrows the transferability of the results. As a theoretical contribution, this paper introduces the concept of AM value chain adoption. The value-adding potential of AM is identified, and the required value-adding activities in collaborative innovation are reported. As a practical implication, the study reveals how companies can learn of AM and adopt AM value chains without investing in AM machines. They can instead leverage relationships with other companies that have the AM knowledge and infrastructure.

Originality/value – This paper introduces AM value chain adoption as a novel, highly interactive phase in the industry-wide adoption of metallic AM. AM value chain adoption is characterized in multi-company collaboration settings, which complements the single-company view dominant in previous research. Theory elaboration is offered through merging technology adoption with external integration from the information processing view, emphasizing the necessity of interorganizational cooperation in AM value chain adoption. Companies can benefit each other during AM adoption, starting with identifying the value-creating opportunities and applications for AM.

Keywords Manufacturing technology, 3D printing, Additive manufacturing, Value chain

Paper type Research paper

Introduction

The metallic additive manufacturing (AM) industry has been growing over the years, and technology has developed into a considerable alternative when firms select manufacturing methods for their products. The adoption of AM (i.e. incorporating AM into commercial use) happens at different levels: as a concept, as a process innovation and as a product innovation

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(Steenhuis *et al.*, 2020). Therefore, metal product manufacturers that choose AM as a manufacturing method will face all these adoption tasks. This paper focuses on AM adoption in the value chains of large companies.

The process of AM adoption is not limited to a single company but potentially spans the value chain (Steenhuis and Pretorius, 2017). Technology companies have adopted the concept of AM and have started to produce AM machines (Steenhuis *et al.*, 2020). After the market introduction of AM machines, pioneering companies, mostly start-ups, purchased these machines and developed specialized skills for AM, adopting AM as a process innovation (Martinsuo and Luomaranta, 2018). Simultaneously, engineering and design companies have explored AM technology from the perspective of design (Luomaranta and Martinsuo, 2020). As design companies tend not to have their own production capacity or product brands, they need to sell their design services to companies that do. This paper argues that before adopting AM as a manufacturing method for certain products, metallic AM must be adopted as the chosen manufacturing technology not only by larger product manufacturers but also more broadly in their value chains, and both processes and products require innovations.

Previous studies already recognized that manufacturing companies have different options when adopting AM; they can directly procure AM-manufactured components (Oettmeier and Hofmann, 2016), develop and contract AM-manufactured components through a new or existing supply chain (Luomaranta and Martinsuo, 2020) or start AM production internally by investing in AM machines and procuring the required materials (Oettmeier and Hofmann, 2016). Any of these options may require innovations in the supply chains compared to firms' ordinary manufacturing approaches (Luomaranta and Martinsuo, 2020). However, cooperation becomes particularly necessary if a large firm does not invest in AM machines. Involving organizations across the value chain in adopting AM is both challenging and time-consuming, requires targeted efforts by focal firms and requires research that spans the network of firms.

This study investigates metallic AM technology adoption in process and product innovation projects involving different firms in the value chain and is positioned at the intersection of manufacturing technology adoption and value chains. Metallic AM was chosen as the context for its potential centrality in manufacturing firms' value chains (Bogers *et al.*, 2016; Holmström and Partanen, 2014; Weller *et al.*, 2015) and the level of complexity concerning suitable application areas (Azteni and Salmi, 2012; Luomaranta and Martinsuo, 2020). The main goal is to generate insights into the progress of AM adoption during collaborative innovation projects. The focus is on the main research question: How and why do companies adopt AM in their production value chain? The "how" concerns understanding the AM value chain adoption process, and the "why" deals with the benefits and added value of the adopted AM technology. Theory on technology adoption applied to AM will be elaborated and expanded through an information processing view (Galbraith, 1977; Tushman and Nadler, 1978) by acknowledging the uncertainty and centrality of external integration in companies' value chains during AM adoption.

This multiple-case study focuses on innovation projects where large companies require innovations for a certain product and related processes, find partners for the project and recognize AM as the most suitable technology and process solution for manufacturing the product. The companies themselves do not have AM machines or the skills to utilize them, but the partners in the innovation project do.

Next, the relevant literature on AM and innovations, adopting AM in the value chain, and AM product innovations are reviewed. Then, the case study approach is explained, including the introduction of the three cases, data collection and analysis. Analytical case narratives describe how the adoption of AM unfolded from introducing the idea of AM to establishing a new AM supply chain. The findings then report how AM adoption changed operations and added value and how activities were carried out in collaborative settings in the innovation projects. The discussion and conclusions reveal the need to view the adoption of radical new manufacturing technology as value chain adoption.

Literature review

AM and innovations

Innovation, following Schumpeter's (1934) definition, means the introduction of a new good, feature or method of production; the opening of new markets; the acquisition of new material sources; or the implementation of a new organization in an industry (Schumpeter, 1934). AM covers multiple dimensions in the Schumpeterian innovation definition as it is a new technological solution that enables a novel method of production to produce new goods in existing or new market segments. AM as an umbrella term refers to many types of technological approaches that allow building objects by increasing material, such as metals, ceramics, plastics or composites, usually layer-by-layer, directly from digital 3D designs (ASTM, 2012; Holmström and Partanen, 2014).

Besides technology innovation, AM can be viewed as a systemic innovation as its large-scale benefits can be achieved only when the technology is complemented with various product, process and service innovations (Martinsuo and Luomaranta, 2018). AM has the potential to impact value chains by much more than simply replacing one machine with another in the production process (Stentoft *et al.*, 2016). Systemic innovations involve multiple mutually influencing, interconnected innovations as part of a broader system (Mulgan and Leadbeater, 2013) that require collaboration in the business network (Chesbrough and Teece, 2002). Reaching competitiveness requires that companies join forces in a broader national or local innovation system where resources, demand conditions, competition and supportive industries jointly drive innovation throughout the value chain (Porter and Stern, 2001). Systemic and fast-developing technologies allow firms to collaborate and build on the strengths of other firms and, thus, legitimize the new technology, establish new industry standards and create a bandwagon effect (Chesbrough, 2003; Garud *et al.*, 2013; Van de Ven, 2004).

Adopting AM in the value chain

AM, as a systemic innovation, has different stages in which it must be adopted (Steenhuis *et al.*, 2020). After the invention of AM technologies, materials and software, the concept of AM is adopted by companies that produce AM machines commercially. They then sell these machines to companies that adopt them into their production of prototypes or commercial goods. The final stage is for customers to adopt products manufactured with AM (Steenhuis *et al.*, 2020).

Despite the growing number of studies on AM adoption, the actual organizational process for adopting AM is poorly understood. Several studies map certain factors and drivers of or barriers to industrial AM adoption (Chaudhuri *et al.*, 2018; Cohen, 2014; Delic and Eyers, 2020; Fontana *et al.*, 2019; Marak *et al.*, 2019; Martinsuo and Luomaranta, 2018; Oettmeier and Hofmann, 2017; Schniederjans, 2017; Schniederjans and Yalcin, 2018; Sobota *et al.*, 2021; Tsai and Yeh, 2019; Yeh and Chen, 2018). These studies do not, however, explain the process of adopting metallic AM technology in interorganizational settings. Also, a recent meta-study by Ukobitz (2021) concluded that (perhaps due to the novelty of AM technology in companies) most previous studies have concentrated more on the intention to adopt AM in firms and the barriers preventing it instead of the actual adoption.

Only a few studies cover the actual organizational adoption of AM, focusing merely on a single firm and non-processual albeit metallic AM (Mellor *et al.*, 2014) or polymer AM technology (Sandström, 2016). One study covered an actual metallic AM adoption case in depth and as a process. Rylands *et al.* (2016) concluded that external sources for acquiring knowledge and cooperatively generating new value with a local university by co-creating product innovations with existing products explain the success of AM adoption in firms. Firms may lack the knowledge needed for AM adoption, and collaborating with other organizations with different knowledge and skills could be helpful (Luomaranta and Martinsuo, 2020).

When AM value chains include multiple firms, there is a need to understand the interorganizational cooperation and flows of information necessary for AM adoption. The information processing view of organizations (Galbraith, 1977; Tushman and Nadler, 1978) acknowledges that organizations face various degrees of uncertainty in their tasks and, consequently, experience information processing needs. External (or supply chain) integration – manufacturers' collaboration with supply chain partners and collaborative management of processes (Flynn *et al.*, 2010) – represents one possible means for organizations to increase their information-processing capacity (Srinivasan and Swink, 2015). External integration concerning customers and suppliers has been positively associated with the comprehensiveness of planning (Srinivasan and Swink, 2015) and some aspects of manufacturers' performance (Flynn *et al.*, 2010; Srinivasan and Swink, 2015). Kim and Schoenherr (2018) differentiated between external integration for products and processes and tested their effects on return in contract manufacturing, showing somewhat contradictory results. While none of these studies deal with technology adoption or AM specifically, external integration in line with the information processing view could potentially explain some challenges in AM adoption and help in developing new knowledge, particularly on AM value chains.

To conclude, previous studies on the organizational adoption of metallic AM are limited to single organizational settings and the intention to adopt instead of adoption progress or success. This research fills the gap concerning completed AM value chain adoption in interorganizational settings by elaborating and expanding the theory of AM adoption with external integration in line with the information processing view and thereby responding to calls by Ukobitz (2021) and Rylands *et al.* (2016).

Product innovations for AM

The task causing uncertainty and requiring information processing in AM adoption deals with the product intended to be manufactured. "Product" is used generally by AM manufacturers as anything they manufacture for their customers, whereas for the purchasing customer, it can be a component or part of a broader solution. Finding suitable products to be produced with AM and creating value for the customer have been recognized as crucial for the adoption of AM in the value chain (Luomaranta and Martinsuo, 2020; Martinsuo and Luomaranta, 2018; Rylands *et al.*, 2016; Sobota *et al.*, 2021). A value-focused approach to AM adoption and product innovations means concentrating on the value the new technology can create for the organizations involved. For example, Fontana *et al.* (2019) and Rylands *et al.* (2016) studied the adoption of AM from a value-driven perspective, considering product development and operations levels for a focal firm.

Opportunity recognition and concept development represent key activities for product innovation (Kirzner, 1997; Shane, 2000; Koen *et al.*, 2001). Existing proprietary knowledge plays an influential role in recognizing the potential opportunities of AM technology, and knowledge of customer problems is important in discovering the right products and services with which to exploit new technology (Shane, 2000). These kinds of activities in development projects can be outsourced (Quinn, 2000), but when collaborating with partners in the value chain, trust between organizations becomes an important aspect of AM-related product innovations in the early phase of adoption (Luomaranta and Martinsuo, 2020; Stentoft *et al.*, 2021).

In the case of AM, the phenomenon of opportunity recognition is referred to as application recognition (Fontana *et al.*, 2019), indicating the specific purpose to which AM technology is applied. This is the concept employed in this study. By recognizing the applications, new product (part, component or end-use product) innovations become possible.

With AM technologies, there is an ongoing debate as to whether applications should be recognized and selected based on a need to develop and replace existing traditionally manufactured goods or to produce completely new products. Previous research reports processual models for recognizing suitable existing parts to be converted for manufacturing with AM (Chaudhuri *et al.*, 2021; Knofius *et al.*, 2016; Lindemann *et al.*, 2015). In a top-down process, the search covers the database of a company's products (especially spare parts) and other commonly available databases; key indicators are assessed; and the best part candidates are selected based on their technological and economic feasibility to be converted into AM manufacturing (Knofius *et al.*, 2016). In a bottom-up process, a company's personnel use their knowledge, skills and creativity in a specially designed workshop to assess existing components' functional, geometrical, manufacturability-related and economical aspects to identify possible AM-converted parts (Lindemann *et al.*, 2015). The top-down and bottom-up approaches can also be combined, as illustrated by Chaudhuri *et al.* (2021).

The existing approaches to application recognition do not explain how and why companies decide to use these part identification frameworks, and our study fills this need. Future research directions deal with the limited data availability of products, design for AM and its influence on innovation and combining conventional and AM technologies in product innovations (Frandsen *et al.*, 2020). The systemic nature of AM-related innovations indicates an evident need for further research on AM adoption and application recognition. A systematic analysis of AM value-adding potentials can reveal radically new domains (covering prototyping, enhanced designs, incremental product launch, custom products, improved delivery, production tools and process concentration) and more versatile possibilities for AM adoption across firms in the value chain (Fontana *et al.*, 2019).

This study expands the view of a focal firm to networks of multiple firms. We employ the value chain concept to emphasize the actions and activities during AM adoption (Hansen and Birkinshaw, 2007) but widen the perspective to cover the network of companies in production supply chains.

Research method

Research design

A multiple-case study design was used to develop a new understanding of AM adoption in the value chain. This strategy was chosen because it enables studying the phenomenon in its natural, real-life context with many possible data sources (Piekkari *et al.*, 2009) and provides a holistic explanation of the cases under study (Ragin, 1992). Multiple cases can be jointly studied to compare and complement each other and to offer information on the core phenomenon (Stake, 2005).

Three cases were intentionally selected as they represent ordinary AM innovation projects, concern both product and process innovations and involve multiple firms in the value chain. We sought recently completed AM innovation projects that featured a specific product and included a company network or at least a dyad. Another selection criterion was that AM technology was used in production (i.e. adopted) and not just in development, so the focus is on the end-use components instead of only prototypes. Also, voluntary participation was sought – the key persons were willing to share their first-hand experiences in AM-related innovations.

Cases

Altogether, seven companies were involved in the two innovation projects. Each project includes a focal firm (i.e. a customer who needed the innovated product as part of its core processes) as well as other companies involved in product innovation and manufacturing. The first project (Case 1) concerns the radical re-engineering of an already-existing component that was functionally critical in its final assembly. The component was completely re-engineered for a radically new manufacturing solution of AM; involved four companies (CU1, ID1, AM1 and MM1; Table 1); and used services from one external company (MM2) to post-process the component.

Company	Key informant title	Interview information	Case
CU1 Process plant technology manufacturer Employs 13,000+ people	Development manager	75 min, provided additional documents	1
	Senior chief engineer	35 min	1
CU2 Mass transport and logistics vehicle maintenance and lifecycle company Employs 1,000+ people	Purchasing manager	90 min, provided additional documents	2a and b
	Chief specialist	76 min, provided additional documents	2a and b
ID1 Industrial design and technology development company Employs 400+ people, ca. 10 in the AM team	Head of AM team, AM designer	1st interview 68 min, provided additional documents 2nd interview 61 min	1, 2a and b
	AM designer	80 min	1, 2a and b
AM1 AM contract manufacturer Employs 10+ people	Sales, metals specialist, and industrial designer	43 min	1
	Sales manager	30 min	1
AM2 AM contract manufacturer Employs 5+ people	Founder, technology director and industrial designer	43 min, provided additional documents	2a
	Founder, CEO	76 min, provided additional documents	2a
MM1 Contract manufacturing company specializing in metals Employs 30+ people	Sales director	25 min	1

Table 1. Background information of interviews

The second project includes two subcases (Case 2a and Case 2b) representing two different innovations where obsolete parts were re-engineered. Subcase 2a involved three companies (CU2, ID1 and AM2) in the innovation project, whereas subcase 2b involved only two firms (CU2 and ID1) and used sourcing from one external company (AM3) to manufacture the re-engineered component.

In Case 1, CU1 is a global process plant technology manufacturer selling its own products. CU1 has its own design, manufacturing and assembly units but also sources components, designs and engineering consultations from other firms. In Cases 2a and 2b, CU2 is a mass transport and logistics vehicle maintenance and lifecycle company that repairs and maintains customer vehicles. It usually purchases, or in some cases manufactures, spare parts and does the installation and repair. CU1 and CU2 are in a central position in adopting AM components in their value chain as they fund the project, engineering and design services and finally purchase the new AM components or subcontract their manufacturing.

ID1 has acquired special skills and knowledge about design and engineering for AM and provided expertise in application recognition and product innovation to help CU1 and CU2 in the studied innovation projects. In Cases 1 and 2a, AM contract manufacturing companies (AM1 and AM2, respectively) also took part in the innovation project. In Case 1, two contract manufacturing companies with traditional machinery were additionally involved in the innovation project. All seven companies are headquartered in Europe and operate globally. We focused only on the companies active in the innovation projects and purposely excluded the other possible organizations involved in the supply chains, such as transport firms, material and software suppliers and customers of companies CU1 and CU2.

Data collection

The innovation projects were studied retrospectively. Data were collected from past events by interviewing the persons involved in the projects, as suggested by Thomas (2011). The data were collected using 12 semi-structured interviews and supplementary open-ended discussions after formal interviews with 11 key informants from the involved companies. The interviews were conducted using video conference calls, which allowed the key informants to provide internal company documents to visualize with screen sharing the product innovations and the different phases that took place in the innovation process. These interviews were recorded, resulting in digital video/audio files.

Table 1 summarizes the interviews and background information of key informants and companies. It also explains the companies' involvement in the cases. The key informants all participated in the product innovations and were key specialists and decision-makers in the projects. Additionally, each company's webpages, blogs, videos and webinars were reviewed before the interviews as secondary data and documented in memos.

Data analysis

The data analysis takes the point of view of product innovation and value chain-level actions from the perspective of both intra- and interorganizational processes. Coding was done inductively (Tavory and Timmermans, 2014), acknowledging that the codes and themes emerged from the data, but the researcher's previous knowledge was also acknowledged as influencing the emerging codes. During each interview, handwritten notes of initial ideas for codes and preliminary ideas for analysis were documented to take advantage of the original situation and the situational intuition of the interviewer (Tessier, 2012).

The analysis was conducted using Atlas.ti software, which allowed coding of the interviews directly from the recorded video conference call files. In this way, additional material could be coded, too, which is suggested by Tessier (2012). The most illustrative phrases of codes were then transcribed for the purpose of reporting the findings and giving transparency to the data.

Coding started by identifying actions, events and context (organizational) and existing problems and the value-adding solutions of AM in the value chain important for the innovation projects. Example codes include "proprietary knowledge," "sourcing/creating knowledge," "starting of cooperation," "cooperation," "seeking partners," "industrial context," "AM added value" and "value chain position," which represent ingredients in the adoption of AM into the value chain of product manufacturing company.

Then, the coded actions were organized chronologically into a timeline (Eveland and Tornatsky, 1990). The analysis then proceeded to writing a narrative of each case to serve as analytical presentations of the cases (Munksgaard *et al.*, 2014). The intention was to preserve the in-depth richness of the cases in the analytical descriptions to increase the insights relevant to the cross-case analysis. This approach also enables readers to conduct further interpretations of the cases and enhances the transferability of results (Stake, 2005).

The analysis then proceeded into the cross-case analysis. First, the added value of AM was analyzed inductively. Then, from the timeline of analytical case descriptions, three distinct phases emerged where events and actions took place. The events regarding network structure changes were further inductively coded as "before AM adoption," "during AM product innovation" and "new AM supply chain structure" to address the evolutionary stages of innovation (Eveland and Tornatsky, 1990). The activities were further coded, and the categories that inductively emerged from the data are presented in Table 3. This analysis enabled revealing how the AM adoption proceeded and what drivers and value-adding aspects influenced AM adoption.

In the findings section, analytical case narratives are first presented case-by-case, followed by the cross-case analysis of the value-adding features of the AM. The cross-case analysis then proceeds thematically, concerning the main phases, value chain changes and activities of interorganizational collaboration during AM adoption.

Findings

Case 1: re-engineering essential parts for the process plant machines

CU1 has many complex parts in their machine systems. Most of these parts are hard to manufacture, and their performance can be low due to design compromises and manufacturability issues. CU1 collaborates actively with local universities. Case 1 started when a highly compromised component, a flow manifold (among others), was given to students as a part to be improved in a course assignment. One student group introduced AM to improve performance and enable redesign.

At that time, the component had become too costly, but CU1 continued the development in a strategic AM project. Consequently, a thesis project was started with a local university of applied science. The thesis identified the 10 most promising components where AM could provide extra value for the whole value chain. Eventually, the flow manifold was prioritized and became the first AM component for the process plant machine.

An industrial design and technology development company, ID1, later recruited the thesis worker. After recruitment, CU1 contracted ID1 to develop the AM component idea further as they had already collaborated in other projects. ID1 had collaborated with a local AM contract manufacturer, and they proposed including AM1 in the innovation project. AM1 experimented with hybrid manufacturing, which was only a hypothetical option at the time, which was introduced to them by the manufacturer of their AM machine. AM hybrid manufacturing here meant that two high-tolerance mounting flanges were manufactured from flat metal using computer-controlled machining, and the bigger flange was set up as the building platform of the powder bed AM machine. ID1 then used this approach in the re-engineering process.

According to the key informants in AM1, ID1 and CU1, this was a groundbreaking technical solution to the problem of creating new value with AM. This way, the cost of the component was decreased by 30%, the power loss of the component was decreased by 70%, and a 25% higher volume output was achieved through the AM-manufactured flow manifold. Part consolidation reduced the number of components needed in the assembly from seven to three. Originally, the processing machine required two mirrored parts on the different sides of the machine, but the new design allowed the same part to be used on both sides. This way, the part consolidation resulted in an actual component count reduction from 14 to 3, reducing the assembly complexity.

ID1 was the project leader in that they served as the link between CU1 and AM1; all contributed to the radical re-engineering of the component. MM1 was chosen from among the existing suppliers of CU1 to produce CNC-milled flanges. When the part was developed, tested and ready for production, ID1 helped arrange the new supply chain agreements between CU1 and MM1, AM1 and MM2. The help for arranging the new supply chain included the transaction of final digital designs and specifications for each manufacturing phase in the supply chain.

At this point, CU1's sourcing unit experienced problems because its sourcing processes and information systems were based on blueprints and a single subcontractor per part. Ordering the new AM part would require using a digital 3D design, and this single part was manufactured by three different subcontractors. MM1 then solved the issue with CU1 by scaling down the original 14 lines in the information system into a one-line order. MM1 became responsible for overseeing this new supply chain. This way, the sourcing process in Company C1 was simplified even though they perceived themselves to be in active collaboration with all the companies involved.

Cases 2a and 2b: spare parts redesigned for AM

Cases 2a and 2b have similar features, thus they are reported together. In Case 2a, the product innovation where AM was adopted was a special swivel joint used as a transport vehicle spare part. The swivel joint was originally manufactured outside the EU by casting it in a steel foundry that no longer existed. The quality of the casted spare part for this application was poor, and establishing a new casting supply chain would require batch sizes too large. CU2 wanted to scale down their spare parts warehouse due to these specific vehicles approaching their end of life.

CU2 contracted ID1 to seek a solution for the quality- and supply-chain-related problem of this spare part after ID1 had marketed their AM services to them. The part was considered suitable for AM. ID1 redesigned the part by scanning and measuring the last spare parts in the inventory and modified the designs to improve AM manufacturability. ID1 then sourced an AM contract manufacturer, AM2, to run simulations of the part and propose final design changes to achieve better manufacturability with its AM machine. The first AM-manufactured part was already functional and was tested by customer CU2.

The new AM spare part resembled the original part in costs due to added redesign costs, reduced warehousing and logistics costs and the elimination of customs costs. Its quality exceeded that of the original part. After testing, ID1 handed over the new 3D designs and helped their customers set up the new supply chain with the AM2. The order batch size was reduced from 100 to 4, and CU2 decided to keep one batch of four swivels in its warehouse as the controlling unit for new orders. AM2 now stores the spare part 3D design, and the order is simply and effectively placed digitally.

Case 2b started simultaneously with Case 2a. In Case 2b, ID1 and CU2 together recognized another spare part to be converted to AM as they were running out of the original spare parts. This already-obsolete spare part was a complex mixing wheel with blades used in the vehicle. The last stored spare part was of too-poor quality for the contemporary specifications, and existing blueprints were insufficient. ID1 then re-engineered the part, and as the part was approximately 30 cm in diameter and complex in geometry, AM was soon determined as the suitable manufacturing approach. To design for AM manufacturability, ID1 and CU1 cooperated to measure and model the assembly interfaces for the spare part and added missing information to the blueprints. The challenging geometry of the mixing wheel also required ID1 to run both AM-manufacturability simulations and functional simulations of the assembly.

Consequently, ID1 explored contract manufacturers that could deliver the quality needed. The best option was found in North America. The transportation distance increased, but the lead time decreased considerably, costs were lower and the quality and performance of the spare part were higher. After completing the development phase and arranging the supply chain, ID1's involvement in the project was over. CU2 now has a new supply chain in place, and they will source further spare parts when needed.

Added value of AM

As described above, each case had a problematic component or spare part. Innovation projects considered and exploited AM as potential solutions to the problems. Additionally, new AM value-adding potential was recognized and successfully delivered. Table 2 summarizes the AM added value in each case.

Case 1 suffered from the original component's difficult manufacturability and low performance. AM added value was received through the manufacturing of complex geometry, which eventually led to cost reduction and functionality increase. Case 2a received AM added value through batch size reduction, which resulted in cost savings in purchasing and

Case 1	Old component • Difficult to manufacture (basically manually) • Low performance (bottleneck in its process) • Assembling required manual fitting every time • Parts consolidation: 14	AM component • Easier to manufacture, 30% cheaper than old component • Higher in performance, power loss decreased 70%, output volume increased 25% • Parts consolidation: 3 • Easy design scalability for other configurations in the future
Case 2a	Old part • Low quality • No existing supply chain but the possibility to establish a new supply chain • In potential new supply chain batch size too large for end-of-life maintenance of vehicle fleet	AM spare part • High quality • Cost per spare part same (in a batch of four) compared to casted spare parts (in a batch of 100) resulting in substantial savings (as estimated needed spare parts somewhere between 10 and 30)
Case 2b	Old part • Obsolete spare part, no good blueprints existing • No existing supply chain nor the potential for new supply chain • Hard to manufacture and much manual welding and grinding would become costly • Last spare part in the warehouse was very low quality	AM spare part • Ensures future availability of the spare part • Viable solution to ensure availability of spare parts, as original spare parts could no longer be purchased or could not easily be sourced as manually custom-made spare part • Quality and lead time great • Cost acceptable

Table 2. Cross-case analysis of AM added value

warehousing. Case 2b achieved AM added value through replacing obsolete spare parts and producing them in low quantities. In this way, the cases differed in the main value driver, but they also had commonalities, such as higher quality and functionality compared to the old counterpart.

The different contexts of the cases disclose why the AM added value was decisive. The informants from CU1 explained that all possible savings were sought from production costs due to competition. Also, the continuous development of process plant machines is necessary for the company to retain its market-leader position. CU2, in turn, operates mainly with publicly owned transportation companies. The lifecycles of the vehicles are 30–60 years, and the maintenance activities and spare parts availability of CU2 are expected to serve throughout these lifecycles. However, over time, the availability of spare parts may be endangered. Consequently, the spare parts may need to be sourced from different suppliers using the same manufacturing technologies or, as in this study, be replaced with completely new technologies, as was done in the cases involving CU2.

Value chain changes during AM adoption

Each part chosen for AM design already had a preexisting supply chain set up for ordinary supply and manufacturing, but in Cases 2a and 2b, the product and related supply chain was becoming obsolete. After the innovation project, the old supply chain was discontinued and a new supply chain was established. Figure 1 illustrates the changes in company networks from before AM adoption to the latest version of the supply chain.

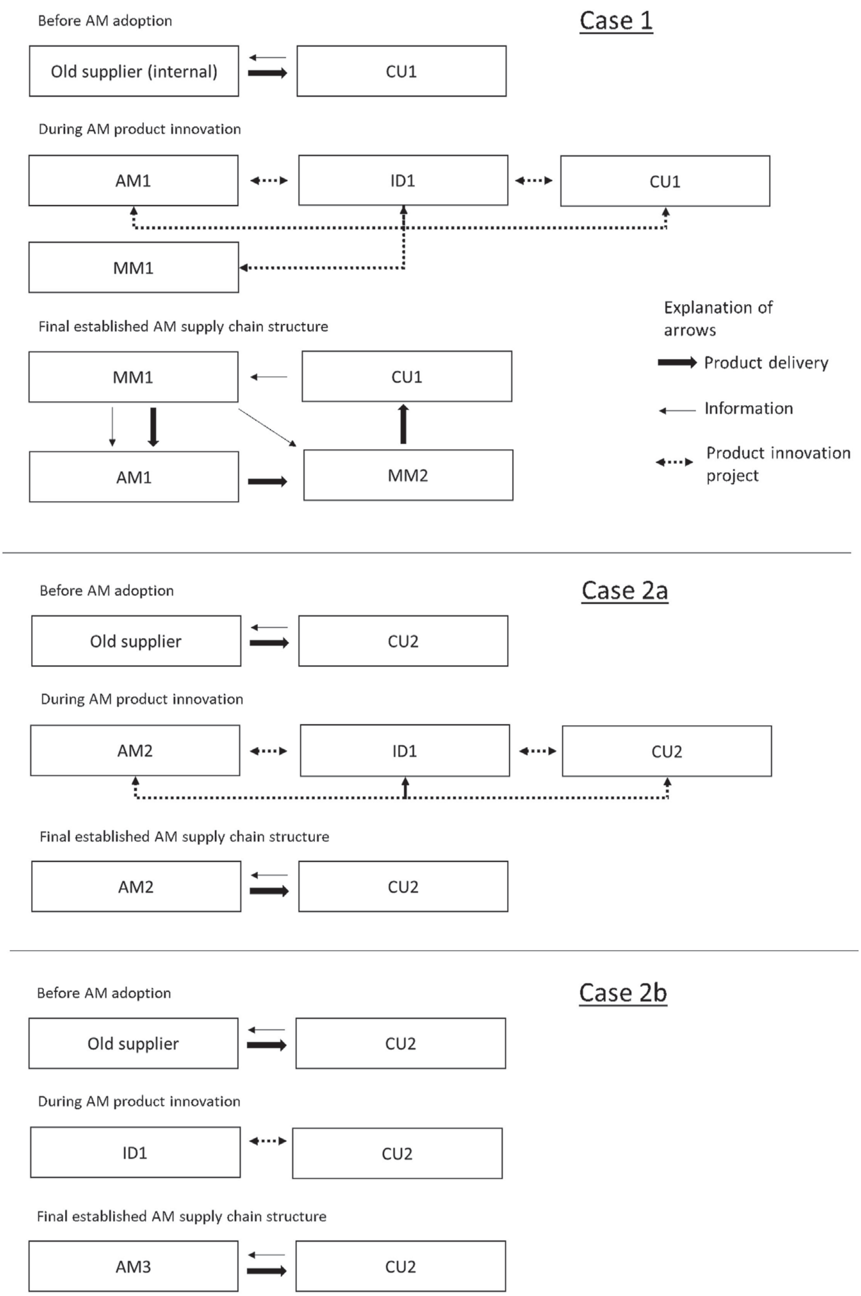

Figure 1.
Illustration of the network structures and the changes

Figure 1 illustrates that ID1 has been in a central position in these innovation projects. Also, other companies (AM1, AM2 and MM1) participated in Cases 1 and 2a, and this highlights the collaborative work that led to the adoption of AM into the value chain of the large manufacturing companies CU1 and CU2.

Activities and interorganizational collaboration during AM adoption

Table 3 clarifies the organizations' cooperation in Figure 1 and activities during the AM innovation project. The innovation projects had approximately the same activities but slightly different involvement and collaboration by companies.

	Activities during the AM innovation project (presented in sequential order, but each activity may have feedback loops to other activities)				
Active companies involved	Starting of collaboration and application recognition	Collaborating for value-based design, potential supply chain partners' identification	Material testing*, prototyping**, demo part testing**	Accepting the design and part characteristics	Establishing supply chain with necessary design and sourcing specifications
Case 1	ID1, CU1	ID, CU1, AM1	ID1, CU1, AM1, MM1	CU1	ID1, CU1
Case 2a	ID1, CU2	ID1, CU2, AM2	ID1, CU2, AM2,	CU2	ID1, CU2
Case 2 b	ID1, CU2	ID1, C2		CU2	ID, CU2

Note(s): * in Cases 1 and 2a, ** in Case 1

Table 3. Activities during the AM innovation projects and interorganizational cooperation

Starting of collaboration and application recognition. Before starting the AM innovation projects, CU1 and CU2 increased awareness about the technologies outside their own organization; as the informant from CU2 stated: "*We have the willingness to keep up-to-date and try different options in the organizational level.*" Informants in CU1 and CU2 explained they had gathered information about AM before these innovation projects to offer services to recognize the applications where AM can provide value through design. CU1 gained experience through university-related collaborations and internal development projects. CU2's informants had participated in local universities' seminars to scout AM possibilities.

For ID1, a knowledge base was built before these projects. Both informants of ID1 expressed that they had a personal interest in the new technology, and through their insights, ID1 was persuaded to establish the AM team. Neither informant at ID1 had received AM-related basic education in their engineering studies, so they educated themselves extensively about AM. Various technology fairs and seminars were useful in exploring new technological alternatives and organizations in the AM industry.

The starting point for collaboration was previous technological knowledge about AM. When ID1 contacted CU1 and CU2, they knew enough about AM to initiate an AM-innovation project once the potential applications were jointly recognized. According to a key informant from ID1: "*To find out the critical aspects where AM can be beneficial is the most demanding part of this process but also the area where our expertise shines.*" This statement highlights the necessity to discover where AM can contribute additional value to even initiate a development project.

Collaborating for value-based design, identifying potential supply chain partners. In the design (or re-engineering) phase, ID1 cooperated closely with their customers, CU1 and CU2, to ensure the functionality and quality of the AM part. With its creative AM design skills, ID1 built on the parameters for the key functionalities from the customers. The product owners (e.g. CU1 and CU2) then had the product, assembly and component-level knowledge.

When these can be aligned between ID1 and either CU1 or CU2, there is a possibility to find out where AM can add value. According to a key informant from ID1, "*the most demanding part of these cooperative projects is to find out what are the actual necessities of the components, is it aesthetics, weight, certain functionality, or cost of manufacturing?*"

As neither CU1 and CU2 nor ID1 expressed an interest in investing in metallic AM machines, ID1 contacted potential AM service providers. AM1 and AM2 were then introduced to the projects and contributed with their AM manufacturability expertise. The informant from AM1 explained: *"we are focusing on the operating of this new technology of AM, and we want to be seen as the experts of this technology,"* and continued, *"if the customer request is a simple task, we do it from scratch to the end. Otherwise, a company like (ID1) is in an important role, a link between us and complex design job*."

Demonstrating, testing and accepting the design. Trust in the new technology was something that had to be gained. The second informant from ID1 explained the centrality of technology trust and the importance of testing in Case 1: *"Customers are quite reserved regarding this new technology (AM) and regarding material properties . . . this customer (CU1) was also reserved regarding the components made with AM, but they were curious, too. So, this was resolved by extensive testing of demo parts and drawbars. All the tests were conducted, the customer tested tensile strengths, examined the fractions, they even grinded them with angle grinder, tested welding and exposed the demo part to extreme conditions, and compared all the results to standard parts. Eventually, the result of these tests corresponded to our machine and material supplier's data sheets."* Drawbars are test pieces manufactured simultaneously with the part or demo that produce the same internal microstructure. Drawbars can then be predisposed to structural testing.

Another example concerning technology trust deals with evidence about product quality. The second informant from ID1 explained this through their experience in collaborating with CU2 in Cases 2a and 2b: *"With them (CU2), we had the data sheets to provide the data that these AM parts actually are very good quality, and we proceeded directly to manufacturing as these spare parts required no prototypes, but the first prints were directly ready for use."*

The difference between CU1 and CU2 concerning trust in AM might stem from the different natures of their businesses. CU1 designs and sells its own solutions – large process plants – that its customers use in conducting their main business. Each solution builds on the proprietary knowledge of CU1. The component re-engineered for AM is an important component in the process. The customer's business would be interrupted if faults occurred, so CU1 had to be certain that the quality was high. CU2, in turn, maintains its parent company's vehicle fleet and has non-proprietary components. The AM spare part was a wearing part anyway, and if it were to break in action, it would be replaced with a spare vehicle while in repair, unlike the case in CU1, where an AM component breaking would lead to the malfunction of a large process plant machine. Consequently, the reputation risks differ between these business environments.

After the completion of the desired value-adding designs, the customer companies (CU1 and CU2) accepted the parts for production. The informant from CU2 confirmed this: *"The designs and data provided looked good, and the manufacturer (AM2) simulated the results of the AM process. We then proceeded directly to ordering the spare parts . . . they are now in use, and we painted them with bright colors, and the routine maintenance pays closer attention to them, but so far everything seems to work fine."*

Establishing the supply chain with necessary design and sourcing specifications. New supply chains were established for AM manufacturing. As AM service providers AM1 and AM2 were already part of the project, they took the role of AM manufacturing after the AM manufacturing contracts were signed. In Case 2b, ID1 arranged a manufacturer for the spare part as AM service providers did not participate in the innovation project. The informant from ID1 explained their coordination role: *"We help in establishing the supply chain so that* *there will be no gaps in, for example, in quality assurance after the component or spare part is design-wise ready and ready for production.*"

The industry of AM service providers and contract manufacturers, however, is still emerging and in transition. Manufacturing standards and operational practices are still underdeveloped, and it is project-dependent who bears the responsibility for quality and what is expected to be delivered by these contract manufacturers. *"At the moment, we are in the situation where if we source a single part with similar 3D models from six different contract manufacturers, we get six different parts. This is not a huge problem per se, but in practice it creates a lock-in situation with one AM contract manufacturer, with whom we did the R&D, if we want to proceed to serial production,*" said the informant from ID1. Through these activities, the AM innovation projects were carried out and ended with functioning new AM value chains.

Discussion

The main goal of this study was to generate new insights into how AM adoption takes place when adopted in the production value chains of companies that do not invest in AM machines and why AM is adopted into the value chain. This study contributes to the knowledge on the adoption of AM through the value-driven potential of AM and answers the call for studies to illustrate successful cases of AM adoption (Luomaranta and Martinsuo, 2020; Rylands *et al.*, 2016; Ukobitz, 2021). We explored companies that cooperate in the value chain to generate new opportunities and analyzed innovation projects as platforms that enable the companies to benefit from each other when identifying value-adding applications and establishing new supply chains. Technology adoption was purposely connected with external integration building on the information processing view to complement single-organization studies of AM adoption.

AM adoption in the production value chain

The main theoretical contribution adds an important stage for the large-scale adoption of AM, namely, the adoption of AM value chains, which connects technology adoption with external integration based on the information processing view of organizations (Galbraith, 1977; Tushman and Nadler, 1978) and lends support to and complements AM adoption research (Steenhuis *et al.*, 2020). For large-scale AM adoption, metallic AM must be selected and adopted in the supply chains of larger product manufacturers, as shown in our empirical study. The studied successful innovation projects showed how such product manufacturers proceeded in AM value chain adoption through a series of activities of problem identification, AM application opportunity and value recognition and value chain changes in collaboration with suitable partner companies.

AM value chain adoption takes place between process and product innovation adoption, where product problem recognition enables the process innovation of utilizing the new technology and developing a possible new structure of the supply chain and where the innovative concept of AM and its process innovations enable value-adding product innovations. The empirical study offers evidence on the temporal order of developing products and processes during AM adoption and related collaboration and, thereby, witnesses complexities identified in external integration in other contexts (Kim and Schoenherr, 2018). This modified illustration of AM adoption stages builds upon Steenhuis *et al.* (2020) and is presented in Figure 2.

The studied innovation projects showed that it is not necessarily large firms but rather pioneering companies (usually smaller) that first adopted AM and purchased metallic AM machines to experiment with the technology, start a new business and acquire new

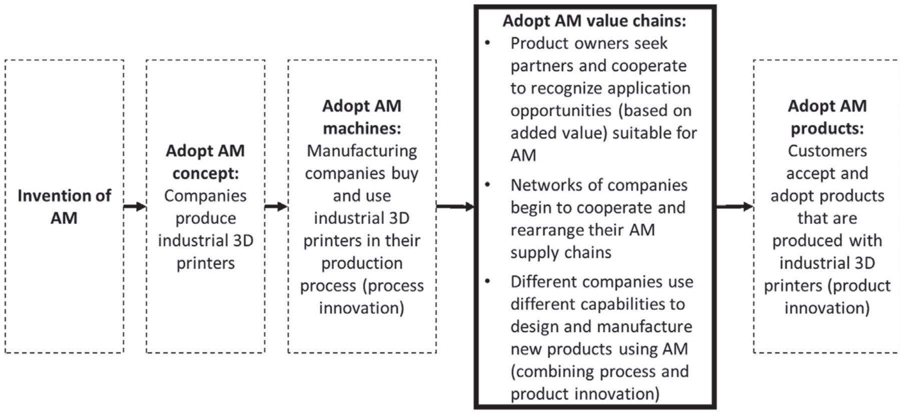

Figure 2. Different stages of AM adoption and the main contribution of this study

Note(s): Modified from Steenhuis *et al.* (2020), dashed line boxes in the original conceptual figure

capabilities to succeed in the competition. These activities fall into the stage of companies adopting AM as a process innovation (cf. Steenhuis *et al.*, 2020). However, companies that do not seek to create a new market with new technology have a completely different perspective, and their AM adoption requires extensive movement in their value chains. For them, the technology and its potential markets are not the reasons for adopting AM into their value chains; rather, their interest is in the value of AM. They need to recognize the right value opportunities for products offered by AM technology compared to alternative manufacturing methods and establish the right fit for their value priorities and situations.

The findings concerning the first part of the research question (how companies adopt AM in their value chain) offer a new understanding of the innovation adoption process, specifically in connection with external integration. The cases revealed the simultaneous occurrence of product and process innovations when firms that did not invest in AM machines decided to adopt AM in their value chains. This indicates that successful AM adoption requires comprehensive planning, seen as an important mechanism for uncertainty reduction when integrating external partners in the supply chain (Srinivasan and Swink, 2015). Before customers adopt AM products, metallic AM value chains require significant innovation steps in cooperation between brand-owning manufacturing firms and their partner companies. While the product re-engineering that took place in the cases might be considered incremental innovation, the required process innovation is radical, as it is new to the industry and potentially also to the technology supplier, requiring intensive cooperation between the firms (Chaoji and Martinsuo, 2019). Radically new approaches were needed for recognizing the value potential of serving customers in a new way, recognizing and selecting the application suitable for AM and designing the manufacturing process and production value chain for AM.

The findings for the second part of the research question (why companies adopt) – specifically, companies' motivation to adopt AM – concentrate on the value AM can add. The identified value drivers dealt with the companies' unique business contexts and problems concerning previous components or spare parts. The solutions for these problems and other benefits (i.e. added value) were possible to realize with AM, lending support to other AM-value-related research (Fontana *et al.*, 2019; Rylands *et al.*, 2016).

Interorganizational cooperation for product innovation

The findings showed successful examples of innovation projects that featured an evolutionary process of interorganizational cooperation (Figure 1 and Table 3), the value-driven recognition and design of AM products (Table 2) and establishing new supply chains for new AM products (Figure 1). Thereby, the examples offer evidence of the unfolding of adoption processes for systemic innovations in interorganizational networks (cf. Garud *et al.*, 2013; Chesbrough and Teece, 2002) and the benefits of external integration in the form of better information processing capacity for manufacturing firms when the task of product and process innovation is highly uncertain (Flynn *et al.*, 2010; Srinivasan and Swink, 2015). AM was completely new to companies CU1 and CU2, and eventually, they adopted AM into their value chains successfully. However, AM value chain adoption required the involvement of multiple actors in innovation projects. AM application recognition, value-driven design for AM, design for AM manufacturability and establishing supply chains were central activities in driving success in AM value chain adoption for these larger companies.

This finding contributes to Fontana *et al.* (2019), who emphasized the importance of finding the right applications and recognizing AM added value. In Case 1, the AM added value stemmed from the possibility for AM to manufacture complex geometries, leading to cost reduction and increased functionality (supporting Fontana *et al.*, 2019 on enhanced designs, process concentration and improved delivery). In Case 2a, the AM added value dealt with batch size reduction, which resulted in cost savings in purchasing and warehousing (improved delivery in Fontana *et al.*, 2019). In Case 2b, the AM added value was AM enabling the production of a low quantity of highly complex obsolete spare parts where there was virtually no other option left (improved delivery, process concentration and enhanced design in Fontana *et al.*, 2019). Depending on the whole value chain and the context, there might be the possibility (or need) to cover multiple value-adding prospects of AM.

When designs of process plants are established, radically re-engineering components or converting obsolete parts for AM will likely offer many future application opportunities for AM. In this sense, replacing already-existing parts and components can, based on our findings, enable companies to build knowledge about AM, and this is relevant for the early phase of AM value chain adoption. This replacement requires the re-engineering of parts and components (Frandsen *et al.*, 2020). The exploration of the potential of AM in future industries will also create radical product innovation possibilities for AM as completely new products are yet to be invented (Fontana *et al.*, 2019).

The analysis of the cases offered additional information on the challenges of application recognition and design for AM, contributing to Fontana *et al.* (2019). The existing frameworks for recognizing AM products (Chaudhuri *et al.*, 2021; Knofius *et al.*, 2016; Lindemann *et al.*, 2015) were to some extent known by ID1 and helpful for building knowledge, but the innovation processes proceeded in a much more *ad hoc* manner than suggested by the frameworks. Application recognition requires the expertise of design companies as they have the knowledge and skills to design AM and the knowledge of their clients' products. This competence base is useful for executing customized application recognition processes that are currently out of reach for manufacturing firms or companies specializing in operating AM machines. Stentoft *et al.* (2021) similarly found that other organizations in the adopting companies' networks are a good source of knowledge required for AM adoption. The expertise and skills needed for AM are not only in the operation of the actual machines but also in being able to design new products and innovate new applications, which will benefit from the technological possibilities of AM technologies (Luomaranta and Martinsuo, 2020).

Companies adopting AM in their value chains face the legacy of earlier technologies, both as a possibility to extend product lifecycles and as a necessity to replace outdated components and related supply chains (Ballardini *et al.*, 2018). Cases 2a and 2b herein illustrate this kind of situation, where the lifecycle of the repaired vehicles with AM spare parts can now be extended by several years, and the quality of AM spare parts is superior to that of old spare parts. Various issues will need to be resolved in spare parts production for systems with long lifecycles. AM spare parts can be a feasible solution for repairing or extending the lifecycles of machines where the spare parts supply has become obsolete, but it may introduce new quality problems or increase costs (Ballardini *et al.*, 2018). Although the cost per part might be higher for AM spare parts in their small batch sizes compared to casted spare parts, the actual need for so few spare parts favors AM. Ballardini *et al.* (2018) and Frandsen *et al.* (2020) also raised the topic of missing computer-aided designs of spare parts, which needs to be resolved. Cases 2a and 2b also offer insights into how a dedicated design company (ID1) was able to re-engineer parts in a situation where there was only an old paper drawing and one low-quality spare part left for demonstration.

Conclusion

For the large-scale adoption of AM, AM concepts, products and processes need to be broadly accepted in the production value chain. Case studies of successful AM adoption have been called for (Luomaranta and Martinsuo, 2020; Ukobitz, 2021) to overcome managers' AM technology trust issues and further advance the adoption of AM. Our multiple-case study generated new knowledge on application recognition and interorganizational cooperation during innovation projects when adopting AM in companies' production value chains. The findings showed that the adoption of AM happens through successful innovation projects that cover both product and process innovations and take place in a collaborative project setting.

The first theoretical contribution extends and elaborates the process of technology adoption specifically in AM. We propose the new stage of AM value chain adoption for the existing framework of AM adoption (to add to Steenhuis *et al.*, 2020). This stage is necessary to bridge the gap between consumers' product adoption and manufacturers' technology adoption because AM alters production value chains and requires simultaneous process and product innovations. Firms within AM value chains will need to realize the potential of cooperation when adopting AM. As not all manufacturing firms are procuring and installing AM machines themselves or replacing their existing technologies, they will benefit from cooperating with other AM firms in selecting, designing and manufacturing products optimized for AM and also offer new value to customers.

The second theoretical contribution elaborates the information processing view (Galbraith, 1977; Tushman and Nadler, 1978) specifically in the context of AM innovations. Merging technology adoption with external integration from the information processing view enabled emphasizing the necessity for interorganizational cooperation in AM value chain adoption, which is a complex process and an uncertain innovation task spanning across organizational boundaries (Garud *et al.*, 2013; Chesbrough and Teece, 2002). The collaboration with other companies allows a company with little knowledge of AM to leverage the knowledge of other companies and combine it with proprietary knowledge (supporting Chesbrough, 2003; Van de Ven, 2004). This external integration through collaboration enhances the company's information processing capacity and enables managing the uncertain task of product and process innovation (in line with Srinivasan and Swink, 2015).

The third contribution is in explicating and showing evidence of the technical and business value of AM as a driver of successful AM value chain adoption. We showed how AM was able to add value compared to the alternative manufacturing methods in terms of cost, functionality, quality and availability, and this identification of added value was required for the successful adoption of the AM value chain. These findings add to earlier research on the application selection and value-driven innovation in AM (Ballardini *et al.*, 2018; Fontana *et al.*, 2019; Rylands *et al.*, 2016) by explicating the necessity to consider processes and value chains simultaneously with product innovations.

As a practical implication, this study encourages companies to educate themselves about the characteristics of AM, which will help in recognizing applications where AM can generate value for value chains. The cases illustrated how such innovation projects can be carried out in collaborative settings where project partners' knowledge and skills contribute to the application recognition and value-driven design of AM products and establishing the new AM supply chain. Regarding novel AM technology, companies that know the possibilities of AM and have the skills to identify possibilities for adding value to the application are potential collaboration partners for companies pursuing AM adoption.

The case study approach as a research design has its limitations, including those concerning the choice of cases, limited qualitative data and the framework chosen for the analysis. This study was conducted in two different industrial settings between companies accustomed to subcontracting and collaborating with other companies, and the transferability of the results primarily concerns such environments. Future research might consider conducting further case studies of successful AM adoption through innovation projects in other types of business environments and potentially focusing specifically on the knowledge, capabilities and skills of the organizations. Another interesting venture would be to study the completely new unique manufacturing context that AM opens.

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About the authors

Toni Luomaranta, M.Sc. (Tech) is Doctoral Researcher in the doctoral program of Business and Technology Management at Tampere University. His research is focused on value chain changes, manufacturing technology innovations and responsible innovations, particularly concerning additive manufacturing. Toni Luomaranta is the corresponding author and can be contacted at: toni.luomaranta@tuni.fi

Miia Martinsuo, D. Sc. (Tech.), is Professor of Industrial Management at Tampere University. Her field of research and teaching is project and service business. Prof. Martinsuo has over 15 years of academic experience in project and service business, and 9 years of industrial experience particularly in organization and process development in the metal and engineering industry. Her research interests include project-based organizing; steering and selecting product development project portfolios; managing manufacturing and process innovations; industrial service operations and innovations; and organizational transformation toward service business.