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3D Printing and Supply Chains of the Future

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Sebastian Mohr and Omera Khan

3D Printing and Supply Chains of the Future



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Sebastian Mohr and Omera Khan

When discussing emerging supply chain trends of this decade 3D printing (3DP) has become one of the most disruptive phenomena to impact supply chains and the global logistics industry. The technology has already made a notable impact in the manufacturing sector and is now starting to enter homes and schools as well. However, while the expansion of 3DP into the private consumer sector is an interesting development in its own right, the biggest potential for disruption clearly lies in the industrial applications and how they will influence supply chains in the next decade. This study reveals that various points of the supply chain are likely to be impacted by 3DP.

Among the findings are such examples as the implications for inventory and logistics, its contribution to mass customization and portable manufacturing, the relevance for digital supply chains and other supply chain trends such as cloud manufacturing. Thus this study highlights a key trend that will significantly shape and influence the next decade for logistics and supply chain.

This study utilizes primary and secondary data. First, the extensive amount of literature that is available for supply chains and 3DP alike is analyzed. Then, connections between the technology characteristics and current supply chain trends are drawn, uncovering potential impact areas. Secondly, in-depth interviews are conducted with supply chain managers from different industries to gain first hand insights about the current impacts of 3DP. The analysis examines both opportunities and risks emerging from this technology.

Keywords: 3D Printing, Supply Chain Risk Management, Technology Impact, Industry Study

1 Introduction

3D printing has accelerated strongly in recent years (Wohlers, 2014). The technology has come a long way from simple prototyping to fully integrated utilizations in direct manufacturing and because of its many forms of application, 3D printing is said to be one of the most significant industrial developments of this decade (Manners-Bell and Lyon, 2012). This has lasting implications on many companies in multiple industries such as production, research, business development and design (Cohen, Sargeant and Somers, 2014). The impact of the technology on supply chains in particular has been very strong and gave rise to new opportunities but also new risks in this discipline.

Wohlers (2014) anticipate that the global market size for 3D printing will grow from 3 billion USD in 2013 to 13 billion USD by 2018, and surpass 21 billion USD by the year 2020. Gartner reports similar numbers, forecasting the market to reach a size of 13 billion USD in 2018 (Basiliere, 2013). These numbers clearly show that the consensus among experts is that this technology is expected to keep growing, which makes it an important element in the future of supply chains. This is why supply chain managers and academics alike must follow the trends and developments of this technology closely. This is the motivation for this research study.

The ongoing increase in market size is driven by the sheer variety of opportunities that 3D printing holds. The spectrum of applications ranges from simple modeling tools used by hobbyists in their own home, over specialized machines that create replicas of products as testable prototypes in the development department of companies, to sophisticated industrial printers that are used for the direct production of finished components (Cohen,

Sargeant and Somers, 2014). Likewise, there is an abundance of producers of 3D printing machines, spanning models that are targeting the commercial market exclusively, and models that are focused on high-end industrial use (Parker, 2014). This diversity has enabled the technology to find its way into many areas of both commercial and private use.

Numerous cases from the industry especially in the global manufacturing sector are proof of the ongoing success of 3D printing. Large global manufacturers such as General Electric, Siemens and Airbus are using the technology to produce fuel nozzles (General Electric, 2015; Catts, 2013), gas turbine components (Kleinschmidt, 2014) and aircraft parts (Airbus, 2014; Simmons, 2015). Other firms like the automotive company Ford use the technology to produce tools for their production process, such as molds for casting (Ford, 2015). The consumer industry is embracing 3D printing in various ways as well, with the candy goods manufacturer Hershey's employing the technology to create customized pralines (Goldin, 2014), and IKEA experimenting with 3D printing in the context of design and the concept of the connected home (Fawkes, 2014).

Academic research about 3D printing has accelerated alongside the emergence of the technology in recent years, and while the topic of supply chains has increasingly gained more attention in this respect, it remains an area that is largely underdeveloped compared to other domains. Therefore, there is a strong need to address the underrepresentation of research that is specifically concerned with the impacts of 3D printing on supply chains and supply chain management. This study attends to this issue by focusing its investigation on the impacts of 3D printing on the supply chain. Here, the term 'Impacts' specifically refers to the risks and opportunities

created as a consequence of 3D printing technology. Furthermore, the study makes recommendations on how to manage these impacts.

2 Literature Review

Many of the studies on the common impacts of 3D printing blend in with research about its impacts on supply chains. This is due to the fact that when authors describe the effects of the technology in general, they also touch upon issues that are related to supply chain management (Birtchnell, Urry, Cook and Curry, 2013; Huang, Liu, Mokasdar and Hou, 2013; Rayna and Striukova, 2014). Other publications are concerned with the indirect impacts of 3D printing on businesses and societies, regularly investigating phenomena that are potentially relevant for supply chain management as well (Burke, 2014; Huang et al., 2013; Neely, 2014). These works are supplemented by studies that are focused directly on the impacts of 3D printing on supply chains, of which there are only a few academic works (Bhasin, Bodla, Division. and Phadnis., 2014; Nyman and Sarlin, 2014). Conclusively, a lot of information about the impacts of 3D printing on supply chain management can be gathered from related publications in the academic literature as well as in practitioner journals and periodicals.

Table 1 below shows an overview of the impacts of 3D printing on supply chains as mentioned in the literature, as well as the corresponding authors, their studies and sources which are investigating these topics in their respective publications.

Table 1 Overview of the impacts of 3D printing on supply chains and supply chain management. Listed in the table are the specific impacts, their corresponding categories and the sources supporting the research on each of them (Source: Created by the author)

Impact	Categories	Sources
Mass customization	Customer co-creation	(Birtchnell et al., 2013; Janssen, Blankers, Moolenburgh and Posthumus, 2014; Kara and Kaynak, 1997; Petrick and Simpson, 2013; Rayna and Striukova, 2014; Tanenbaum, Williams, Desjardins and Tanenbaum, 2013; Tien, 2012; Walter, Holmström, Tuomi and Yrjölä, 2004)
	Maker movement	
	Prosumers	
	Democratization of design	
	Markets-of-one	
	Postponement	
Changing view on resources	Circular economy	(Bak, 2003; Giurco et al., 2014; Janssen et al., 2014; Reeves, 2009; Sacharen, 2014; Wigan, 2014)
	Higher material/resource efficiency	
	Sustainability attitude	

Impact	Categories	Sources
Decentralization of manufacturing	Local sourcing	(Beyer, 2014; Birtchnell et al., 2013; Farrell et al., 2003; Janssen et al., 2014; Kianian, Larsson and Tavassoli, 2013)
	Re-shoring	
	Dispersed manufacturing	
	Reaching disconnected markets	
Reducing complexity	Reducing assembly steps	(Cohen, Sargeant and Somers, 2014; Janssen et al., 2014; Kieviet, 2014; Manners-Bell and Lyon, 2012; Novak and Eppinger, 2001; Petrick and Simpson, 2013)
	Reducing parts and SKUs	
	Reducing the supplier base	
	New design possibilities	
Rationalization of stock and logistics	Print on-demand	(Bhasin et al., 2014; Charon, 2014; Janssen et al., 2014; Lee, 2013; Manners-Bell and Lyon, 2012; Mokasdar, 2012; Walter et al., 2004)
	Shipping designs, not products	
	Digital inventory	
	Change of inventory mix	

Impact	Categories	Sources
Changing value adding activities	New sources of profit	(Cohen, Sargeant and Somers, 2014; Janssen et al., 2014; Kara and Kaynak, 1997)
	New cost base	
	Changing capital requirements	
	Collaborative manufacturing	
Disruptive competition	3D printing services	(Cohen, Sargeant and Somers, 2014; Tanenbaum et al., 2013; Waller and Fawcett, 2014)
	Reduced barriers to entry	
	Niche markets	
	Producer = investor = founder	
	Printing away from control	

2.1 Impacts of 3D Printing on Supply Chains

According to Birtchnell et al. (2013), Janssen et al. (2014), Tuck and Hague (2006) and Walter et al. (2004), by being a very strong enabler of product customization, 3D printing can have remarkable impacts on downstream sections of the supply chain, such as production and distribution. Tailoring individualized offers to each customer and the involvement of clients in design and production activities hold potential for a shift in priorities of cost and profit management, and late stage postponement can make the supply chain more agile and flexible to react to changes in the marketplace.

The effect of 3D printing on supply chain sustainability is under heavy debate. While researchers and practitioners agree that the technology offers various benefits for preserving natural resources and reducing the global footprint of manufacturing companies, whether this is enough for a fundamental shift in attitude towards a more preservative, protective view on natural resources is yet to be confirmed or refuted by additional studies and empirical evidence (Campbell, Williams, Ivanova and Garrett, 2011; Lipson and Kurman, 2013; Nyman and Sarlin, 2014).

The impact on 3D printing on the global setup of supply chains can be very disruptive. With the potential to support reshoring and local sourcing, the technology can basically turn established global supply chain structures on their heads (Nyman and Sarlin, 2014; Lipson and Kurman, 2013). Furthermore, extraordinary applications such as the establishment of supply chains that can reach disconnected markets and remote locations enhance the impact potential of the technology additionally (Cohen, Sargeant and Somers, 2014; Janssen et al., 2014).

Academic researchers agree that 3D printing is a powerful tool to reduce complexity in the supply chain in a variety of approaches (Cohen, Sargeant and Somers, 2014; Janssen et al., 2014; Nyman and Sarlin, 2014; Petrick and Simpson, 2013). The initial benefit of the technology lies in the consolidation of components into a single product, which consequently leads to a reduction in SKUs and thus inventory complexity, the removal of assembly and pre-assembly steps, and the potential to reduce the supplier base of the company.

Authors generally agree that the impacts of 3D printing could have devastating outcomes for the logistics and inventory sector (Elms and Low, 2013;

Janssen et al., 2014; Kianian, Larsson and Tavassoli, 2013; Manners-Bell and Lyon, 2012; World Economic Forum, 2013). Through the enablement of reshoring and local-for-local manufacturing hubs, 3D printing could initiate a reduction in demand for global transportation, supported by a substitution of physical flow by digital file transfers. Lastly, inventory could be affected by the on-demand production possibilities of 3D printing, and the change of inventory mix can have lasting effects on supply chains and supply chain management as well.

Many authors accredit 3D printing with notable potential to impact the way supply chains add value within many of its sections (Geelhoed, 2014; Petrick and Simpson, 2013; Tudball, 2013). Especially the manufacturing sector could experience significant changes initiated by the technology, such as the emergence of new 3D printing services and other business models like collaborative manufacturing and small scale production.

Academic research reveals that the impacts of 3D printing on the competitive situation in the manufacturing sector can have lasting effects on existing supply chains (Birtchnell et al., 2013; Campbell et al., 2011; Petrick and Simpson, 2013). In addition to that, these impacts can also lead to the creation of new supply chain concepts such as small maker businesses that are based on direct delivery through express services. These companies could be funded through crowdsourcing, and compete in niche markets for a very small group of customers.

2.2 Findings of the Literature Review

Reviewing the literature regarding the impact of 3D printing on supply chains has revealed that the consensus among researchers and practitioners is that the technology has enormous potential to reshape the landscape of supply chain management. Many studies show that part of this potential has already materialized especially in the manufacturing and design sections of the supply chain, but much of it remains untapped. The future impact of the technology on supply chains strongly depends on the various risks and opportunities, which are explained in many of the publications, and to the development of which close attention must be paid by academics and practitioners alike.

The findings of the literature review are shown in Figure 1.

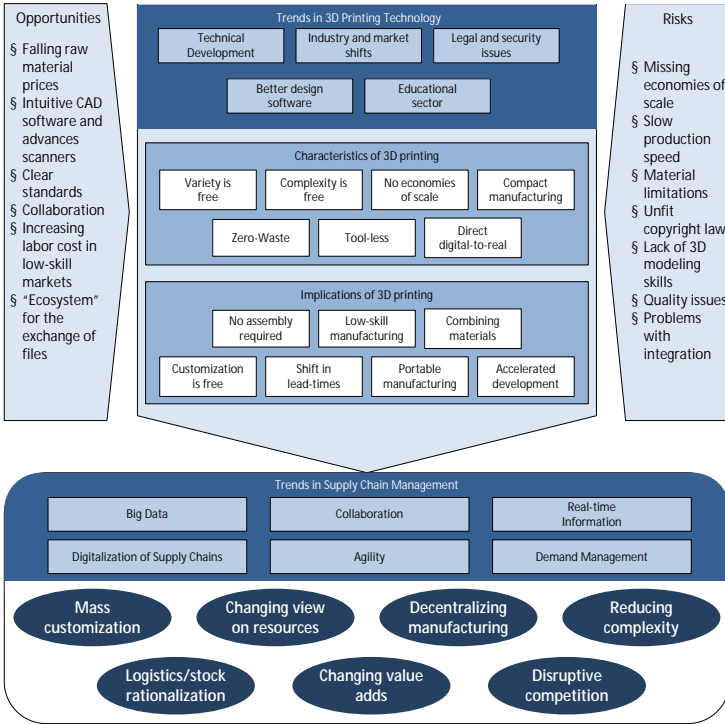


Figure 1 Summary of the literature review, showing how barriers and enablers affect 3D printing in impacting supply chains. (Source: Created by the author)

3 Methodology

The aim of this study is to investigate the impacts of 3D printing on supply chain management, and to identify the risks and opportunities that companies in different industries face from this technology. The aim is furthermore to analyze how companies manage these impacts with means of leveraging opportunities and mitigating risks.

Thus, the scope of this study covers three subject areas: 3D printing technology, supply chain management and the management of risks and opportunities. It addresses the knowledge gap in the academic literature regarding the impacts of 3D printing on supply chains, and gives insight into the topics that are valuable to practitioners of supply chain management as well as scientists from the same area of expertise.

The subject areas and scope of this study as described above are illustrated in Figure 2 below.

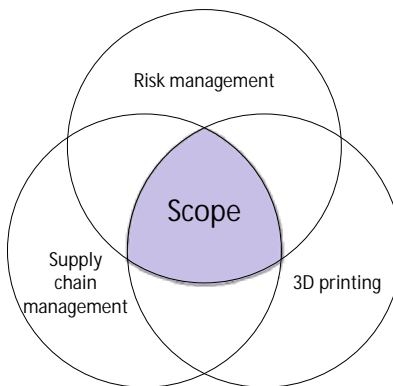


Figure 2 Three subject areas and scope of this study (Source: Created by the author)

In order to follow a structured approach towards filling the scope of this study, the overarching aim is divided into three research questions. Each of these questions targets the information that is required in order to achieve the aim of the study.

- RQ1: What are the impacts of 3D printing on supply chains and supply chain management?
- RQ2: What are the resulting risks and opportunities emerging from 3D printing for supply chains?
- RQ3: What actions do companies take to respond to these risks and opportunities?

Secondary data for this study was acquired through an extensive literature review. For this literature review, the main resources were the online literature databases of the Technical University of Denmark Findit (Technical University of Denmark, 2015) and Google Scholar (Google Inc., 2015). In order to supplement information from the literature with primary data, the method of open-ended, qualitative interviews has been chosen.

3.1 Extended Research Framework

The utilization of the appropriate techniques and strategies that are required in order to fulfill the research objectives, answer the research questions, and ultimately achieve the aim of this study are illustrated.

Figure 3 below shows the extended research framework including all the elements and the structure of this study.

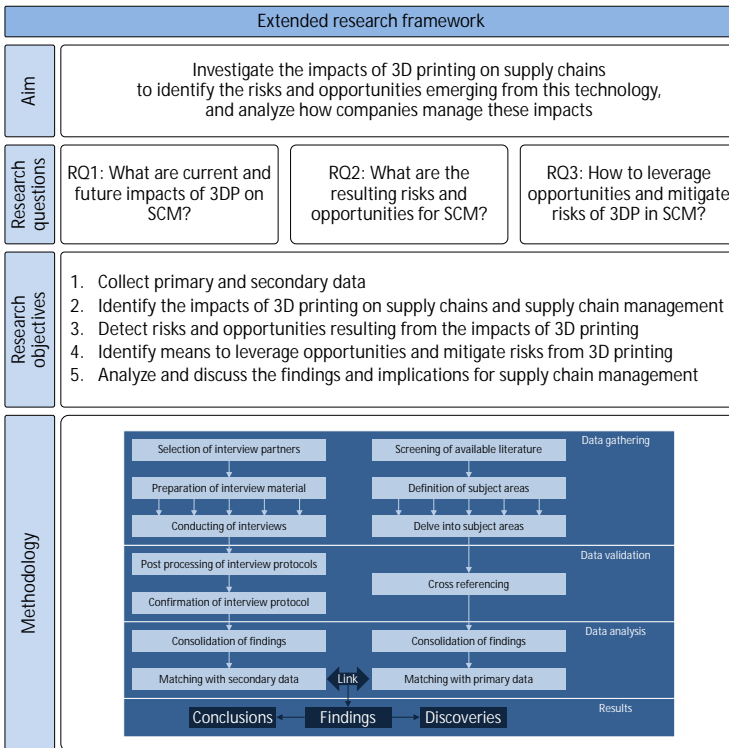


Figure 3 Extended research framework (Source: Created by the author)

3.2 Company Information

Table 2 Overview of the interview dates, times and participating organizations and people (Source: Created by the author)

ID	Date & Time	Organization	Interviewee
01	03-05-2015, 17:00 CEST	General Electric Healthcare	Mechanical and Materials Engineering Manager for X-Ray Tubes
02	27-04-2015, 15:00 CEST	Haldor Topsoe A/S	General Manager – New Business Development Manager
03	26-05-2015, 10:00 CEST	Ford Motor Company	Additive Manufacturing Technical Specialist - Prototype Manufacturing Test and Development
04	28-05-2015, 09:00 CEST	GN	Vice President Global supply chain
05	28-05-2015, 10:00 CEST	GN	Director of Tools and Concept Development
06	25-05-2015, 13:00 CEST	A-dec	Prototype, Test, and Lab Services Supervisor

4 Conclusions

4.1 RQ 1: What are Current and Future Impacts of 3DP on SCM?

Through the investigation of both primary and secondary data in this study, a variety of impacts of 3D printing on supply chain management has been identified. The outcome of the literature review forms the basis for this list of impacts, which is supplemented by findings from the interviews with industry experts. The following is an exhaustive list of the main impacts and their explanations as identified in this study.

3D printing as a manufacturing technology enables companies to customize their products to a very high degree at low cost, and without sacrificing too much efficiency in the production process. This can have significant impacts in the area of mass customization in supply chain management.

Due to the additive nature of 3D printing, the use of natural resources and raw materials is a lot more efficient compared to many other technologies. Thus, with less waste and lower material requirements, the technology has potential to initiate a change in the underlying assumptions about supply chain sustainability.

The high ratio of production volume to space occupied makes 3D printing a favorable option for applications constrained by the limitation of available space. This aspect opens a variety of opportunities in the area of supply chain decentralization and local-for-local manufacturing.

By consolidating parts into single components, and enabling the production of complicated tooling assets, 3D printing enables organizations to reduce the supply chain complexity in their network significantly. This can make the entire supply chain more agile and resilient against disruptions. Utilizing the digital supply chain by sending files instead of physical goods, 3D printing has the potential to rationalize global logistics and inventory activities. This aspect is supported by the on-demand availability of products, and shortened lead-times that 3D printing offers.

Because 3D printing holds the opportunity to turn manufacturing on its head, value adding activities across the supply chain could essentially be redefined and reprioritized. This can have significant successive impacts on supply chain designs and strategies.

3D printing has enabled small scale manufacturers to establish a viable business model without the need for big upfront capital investments, and thus the technology can reshape the laws of competition in certain industry sectors. This shows the disruptive potential of the technology for domestic and international markets alike.

4.2 RQ 2: What are the Resulting Risks and Opportunities for SCM?

The analysis of the impacts that were identified in this study revealed that a variety of risks and opportunities are attached to each of these impact categories. These risks and opportunities are very much dependent on the context of the investigation, the involved parties, their area of expertise as well as the industry sector and business model in question. The following

paragraphs elaborate on the key risks and opportunities that were uncovered in this study.

The perception whether an impact of 3D printing on a supply chain represents a risk or an opportunity is subject to the evaluation of the outcome of this impact. For example, the opportunity of rationalizing logistics and inventory is to reduce the supply chain cost base by saving cost on labor, storage and transport, but the risks of this impact are major layoffs and a reduced safety stock for periods with peak demands. Furthermore, the decentralization of manufacturing in favor of a local-for-local approach holds the opportunity for supply chains to be more agile in the marketplace and having lower logistics cost, but at the same time it bares the risk of increased manufacturing cost and missing economies of scale. Lastly, in-house prototyping is a great opportunity for the focal company to reduce cost and shorten lead-times, but a trend in this direction is likely to have strong negative effects on the prototyping services industry. These examples illustrate that the context of the evaluation is critical when defining risks and opportunities of 3D printing for supply chain management.

Furthermore, there is a variety of tradeoffs between risks and opportunities that are connected to certain impacts of 3D printing on supply chains. In these cases, it is crucial to identify both positive and negative aspects of the impact, and include them equally in the assessment. For example, while 3D printing has the potential to reduce supply chain complexity by consolidating parts and inventory, testing and quality assurance processes can be a lot more complicated as a result of using this technology, which increases downstream supply chain complexity. Moreover, for product design, 3D

printing can significantly reduce supply chain lead-times by producing prototypes quick and inexpensive, which can speed up the entire development process. However, these changes in the process can lead to the creation of other bottlenecks in the process, which can in turn have a negative effect on lead-times. Lastly, one of the key benefits of 3D printing is the resource efficiency of the technology, holding the opportunity for improved supply chain sustainability. However, because 3D printing enables engineers to do more iteration steps while creating and testing prototypes, using more material in the process bares the risk of negative impacts on supply chain sustainability as a potential consequence. The examples in this paragraph show that many of the impacts of 3D printing on supply chains are in fact tradeoffs between risks and opportunities.

Nonetheless, while some of the impacts require an evaluation in the context of different environments and perspectives in order to determine whether they can be categorized as risks or opportunities, in many cases the assessment is more straightforward. For example, mass customization with the help of 3D printing and the resulting trend towards customer co-creation is a big opportunity for the manufacturing sector to serve what has become known as markets-of-one. Companies can utilize a high level of late stage postponement with 3D printing to serve their customers, which is an opportunity for better agility and flexibility of the supply chain. The technology also holds opportunities for new sources of profit, a focus on the key value adding activities in a supply chain as well as new possibilities in product design. In contrast to that, the main risks of 3D printing are the

lack of quality and accuracy for advanced applications as well as the uncertainty about the future technical developments and the corresponding financial risks of an investment.

4.3 RQ 3: How to Leverage Opportunities and Mitigate Risks of 3DP in SCM?

The previous section lists the risks and opportunities that are emerging from the impacts of 3D printing on supply chain management. The analysis in this study has revealed a variety of actions that can be taken in order to leverage the benefits and mitigate the risks. Especially during the expert discussions with company representatives from the industry, many best practices of supply chain management and 3D printing have been discovered. The following is a comprehensive summary of these actions.

In order to leverage the benefits of 3D printing for a supply chain, the technology requires the responsible supply chain manager to have a clear vision for its purpose as well as dedicated leadership from high level management for its integration. Acceptance for the technology must be ensured by educating and informing all involved parties about the intended role of 3D printing in the supply chain, as well as by a clear ownership of the technology by supply chain managers. Failing to do so can result in the cancellation of projects or in ignoring the opportunities of the technology altogether.

By utilizing the reduced labor requirement of 3D printing, supply chain reshoring and offshoring initiatives can benefit significantly from the technology. The case example from one of the participating companies illustrates how a 3D printing driven manufacturing setup in a low-cost country

enabled their organization to reduce supply chain lead-times to as low as a five day turnover. The key to success in this case was the identification of the output as a highly customized product, for which 3D printing is a very favorable manufacturing method. Other leveraging factors include the re-design of products to circumvent shortcomings of the technology in terms of production speed as well as a focus on value adding activities in the home market.

Knowing the limitations of 3D printing, and thus defining a suitable purpose for the technology within supply chain management is essential for avoiding potential risks for the supply chain. Many experts have identified the material quality of 3D printed parts as one of the key issues, but few have suggested or implemented mitigating actions to solve this problem. One of the companies in this study has managed to bypass this issue by using the technology for indirect components that are not part of the final product. This solution can help realizing opportunities in a variety of fields, such as the production of tools, supporting structures and equipment for the testing and cleaning procedures of parts.

In preparation for the risks and opportunities of 3D printing, it is critical to include all potential impacts of the technology on a supply chain in the evaluation process. Many of the implications that are the result of an integration of 3D printing into a supply chain setup are not immediately obvious and can have largely disruptive impacts, if they are not uncovered in phases early on during the assessment. An end-to-end supply chain perspective is therefore necessary to identify all risks and opportunities, and develop appropriate actions. This practice is important, irrespective

whether the area of impact is supply chain cost, complexity, leadtime or flexibility.

Using the unique capabilities of 3D printing to differentiate it from other manufacturing techniques is an essential element for leveraging the opportunities of the technology for the supply chain. Two of the biggest advantages of 3D printing are the freedom of complexity and the freedom of variety, which makes 3D printing a perfect method for applications that require a high degree of customization or a high degree of structural complexity in the components, or both. Many of the industry experts who were interviewed in this study have identified this aspect, and are using the technology for the best possible applications, such as direct manufacturing of highly customized products, tooling or prototyping in the development process.

4.4 Conclusions

In investigating the impacts of 3D printing on supply chains and supply chain management, this research project has explored a new scope of research as defined by the aim of the study presented in the methodology chapter earlier. The aim of this study focuses on the intersection between three distinct research areas: supply chain management, 3D printing and risk and opportunity management. Thus, one of the theoretical contributions of this study is the opening of a novel scope of investigation in the academic field.

Furthermore, the basic and the extended version of the research framework that are presented in the methodology of this study were developed

specifically for this research project. Therefore, these frameworks represent an important contribution in the form of an addition to the scientific methods and materials that are used in the context of research about the topic of 3D printing impacts on supply chains. Thus, the development of these frameworks is an additional theoretical contribution of this study.

Finally, the results from this study can serve as a valuable basis for further research in the scientific area of the impacts of 3D printing and corresponding risks and opportunities for supply chains. The findings that were uncovered herein present a comprehensive collection of insights about the research area. At the same time, the gaps between literature and industry that have been uncovered by this research project leave open opportunities to expand the body of knowledge in breadth and depth.

To summarize, this research project has filled a gap in the academic literature that is characterized by the intersecting scientific subjects of 3D printing, supply chain management and risk and opportunity management. This is an important addition of knowledge to the academic sector, and thus forms the key theoretical contribution of this study.

The main practical contribution of this study is tied to the findings of the literature review and the analysis, namely a listing of potential future impacts of 3D printing on supply chain management. First and foremost, the literature review herein provides an extensive evaluation of the current state of knowledge in academia about the research topic. It lists potential implications of 3D printing as identified by scientific authors, and translates these implications into impacts on supply chains in the future from an academic perspective.

Furthermore, the analysis in the previous chapter supplements the theoretical findings about the research topic with practical insight from industry experts, therefore providing an understanding as to how the practical perspective of this research topic fits into the overall body of knowledge. This comparison, which is drawn between the scientific and industrial sector, results in the identification of risks and opportunities emerging from the technology, and in addition, discovers best practices and actions to mitigate the risks and leverage the opportunities of these impacts. This information is especially useful for practitioners and their applications.

Overall, this study provides comprehensive insight into the future impacts of 3D printing on supply chains by combining primary and secondary data in an extensive and structured analysis. This is a valuable contribution to the practical field of research in this area.

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