Impact of Additive Manufacturing on Supply Chains

Elisa Lauth[1] and Steffen G. Scholz[1,2,3(✉)]

[1] Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshofen, Germany
{elisa.lauth,steffen.scholz}@kit.edu

[2] Karlsruhe Nano Micro Facility (KNMF), Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany

[3] Future Manufacturing Research Institute, College of Engineering, Swansea University, Swansea SA1 8EN, UK

Abstract. Technologies are evolving over time and some innovations can result in disruptive changes which lead to transformations in companies and their supply chains. Three-dimensional printing (3DP) has high disruptive potential as it is becoming increasingly relevant as a production technology. Hence, it is of significant importance to investigate the current and future impacts of 3DP on supply chains. The state of the art provides an overview of supply chain management as well as the production aspects of additive manufacturing. Moreover, impact factors of 3DP on supply chains have been identified. To further investigate the current and future impacts of 3DP on supply chains, five interviews with technical experts have been conducted. The analysis of the interviews shows that the companies have sensed changes in their supply chains. However, most of these changes regard prototyping and there have not been drastic changes in the production of end products. Current impacts have been identified in mass customization, resource efficiency, rationalization of inventory and logistics as well as prototyping and product design. Future impact is seen overwhelmingly in all impact areas. Moreover, AM will ultimately increase the sustainability of supply chains. Finally, a recommendation for action can be given for companies to implement the technology in small batch sizes and to consider it as a complementary technology.

Keywords: 3D printing · Supply chain management · Industry 4.0

1 Introduction

As technology evolves over time, new advancements occur. Some of the technological novelties can result in disruptive change [1]. The ongoing technological developments lead to transformations of factories which have impacts on supply chains [2]. Due to the potential disruptive changes, executives must be aware of technological novelties that could impact their organizations and supply chains [1]. Current disruptive technologies are for instance robotics and automation, big data, internet of things as well as three-dimensional printing (3DP) [3].

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3DP which is often used synonymously in industrial context with additive manufacturing (AM) [4] describes a manufacturing technique where objects can be built by the addition of materials [5]. 3DP is experiencing a rapid growth [6] and many companies try to follow this trend and further their business endeavors using this new technology [7].

Due to the Covid-19 pandemic the AM community had the opportunity to help in fulfilling local demand and to test the application of 3DP for industrial use [8]. Although the researchers were able to identify the benefits and the usefulness of 3DP in industrial manufacturing, the impact of 3DP on organizations is still underrepresented in research. Since it is of high importance for companies to be aware of disruptive technologies as well as solutions to cope with them, the present study will answer the following research questions: What are the current and future impacts of 3DP on supply chains?

This paper is structured as follows. Section 2 gives a literature review on supply chain management (SCM) as well as AM. Section 3 covers the methodology applied in this paper which is used to analyze the interviews conducted with five selected companies. Then, Sect. 4 illustrates the findings. Thereafter, in Sect. 5 the impact areas identified in the field research will be discussed and recommendations for action formulated for the coping of disruptive technologies such as 3DP. Finally, Sect. 6 provides a brief conclusion and outlook.

2 Literature Review

2.1 Supply Chain Management

SCM is of high importance in the current business environment. It is generally considered to be one of the best areas which can yield significant advantages over the competition [9], especially due to the optimization possibilities such as cost reductions. Consequently, organizations strive to implement effective SCM [10].

The Global Supply Chain Forum defines SCM as "the integration of key business processes from end user through original suppliers that provides products, services and information that add value for customers and other stakeholders" [11]. Supply chains generally consist of two or more organizations that are linked by information, material, and financial flows. In supply chains there are producing firms that manufacture either components, parts, or end products as well as logistics service provider and customers [12]. In conclusion, SCM generally has three tasks that can be summarized into sourcing raw materials, converting this material into finished products, and then supplying the products. Thus, supply chains can be characterized by a forward flow of material and a backward flow of information [13].

2.2 Production Aspects of Additive Manufacturing

The American Society for Testing and Materials defines AM as "the process of joining materials to make objects from 3D model data, usually layer upon layer" [4]. Hence, AM is a revolutionary technology that allows for the building of physical objects based on digital files [7]. Many scholars consider AM to be a disruptive technology [14]. In

the early stages of AM, its application was mostly focused on prototyping whereas now it has many more applications [15]. With an increase of usable materials, the number of possible applications has risen drastically [16]. Nowadays AM has the potential to impact manufacturing and provide benefits for producing companies [17]. Consequently, many organizations are interested in the possible benefits 3DP could have in their production [7].

Regarding the evaluation of AM, the production technology is considered to be a more agile and eco-friendly alternative to conventional manufacturing. Nonetheless, the slower manufacturing process as well as few adoptions of AM still limit its applications [8]. Hence, AM is more suitable for small batch production [18]. Moreover, decentralized productions, and higher flexibility that can help with mitigating delays in supply chains, and other problems regarding supply shortages, are a clear advantage of AM which makes it a good alternative for conventional manufacturing [19]. Nevertheless, most scholars agree that 3DP will not make conventional manufacturing obsolete but rather complement these technologies [17]. This is likely since both manufacturing methods suit different productions styles.

2.3 Impact of Additive Manufacturing on Supply Chains

Numerous scholars agree on the fact that 3DP has a high disruptive potential regarding its impacts on the logistics industry and global supply chains [20]. As the use of 3DP in the manufacturing and fabrication of goods increases, the possible impacts on the supply chain are of high importance. Especially since it has the potential to presuppose a change in supply chains [21].

The use of 3DP in the production process can be advantageous for many organizations. Principally since it can ensure a complexity reduction of supply chains. Due to the possibility to print on-demand, the need for excessive inventory becomes obsolete. As a consequence, the traditional complex supply chain model is no longer required. In Fig. 1 a new proposed model for supply chains can be seen. As a result, the supply chains with integrated AM become less complex since only the materials along with the digital files are needed for the 3DP. Whereas the focus of traditional supply chains is on the mass-produced goods which are pushed out into the market with high logistics costs and emissions, the supply chain that integrates AM can provide a low volume production with customized products [22].

Apart from the differences in the supply chain structure, seven key impact areas of 3DP on supply chains can be identified. The first impact area concerns the mass customization enabled by 3DP. AM offers the possibility to individualize products for each customer. Due to late-stage postponement customization, the supply chain is thought to be more agile and flexible which ultimately benefits the reaction to late changes in customer requirements [23]. The second impact area of AM is resource efficiency. One of the numerous advantages of AM is the increased resource efficiency of 3DP [8]. Equally important is that the excess material in 3DP can be recycled and reused which endorses the idea of a circular economy. Another important impact area focuses on the decentralization of manufacturing. Due to the possibility to print on-demand, there is a shift of the manufacturing location to the point-of-consumption. This helps in reacting quicker to changes in demand which in turn ensures the flexibility of supply chains [23].

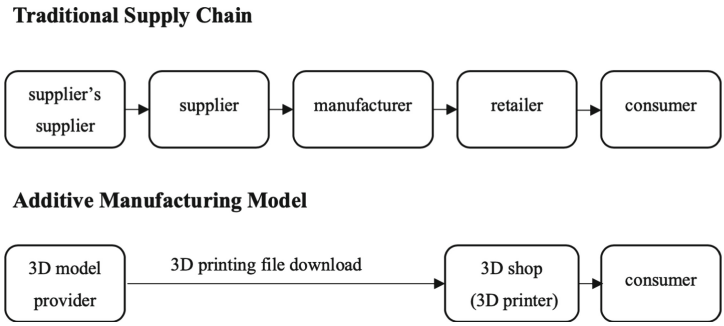

Fig. 1. Traditional supply chain and additive manufacturing model [22]

The fourth impact area is the complexity reduction. Supply chains' complexity can be drastically reduced, which is also apparent in Fig. 1. The consolidation of multiple suppliers and the shortening of the manufacturing process can ultimately lead to reduced complexity as well as shorter supply chains [5]. Equally important is the rationalization of inventory and logistics. 3DP enables the production-on-demand at the point of consumption. This leads to reduced demand for global transportation [23]. Moreover, there is no longer a need for excessive inventories [21]. The sixth impact factor is concerned with product design and prototyping. 3DP allows products to take on new forms which would normally not be possible in traditional manufacturing [24]. Moreover, there is a direct digital-to-physical concept. The last impact factor of 3DP consists of legal and security design. This impact area is concerned with legal issues posed by 3DP. Currently, the underlying legal framework is not sufficient [23].

3 Methodology

This section focuses on the methodology followed in this study. To evaluate the impact 3DP has on supply chains, interviews were conducted with representative industry experts. For the evaluation, qualitative content analysis was used. The qualitative content analysis method deals with text evaluation in the context of research projects [25]. Concerning the data collection, semi-structured interviews will be used. They allow participants to respond freely and to clarify their opinions [26]. Prior to the conduction of the interviews, an interview guide was created [27].

For the present study, the most important criterion for the participants was their involvement with 3DP in their everyday work. As a result, five experts were acquired. All interviewees are from different companies, ensuring diversity in answers and opinions. All information on the interviewees as well as their companies, are anonymized. Nevertheless, the industry sector is briefly explained. The most important information on the personas is summarized in Table 1. The interviews lasted 30–40 minutes.

Table 1. Profile of the interviewees

Interviewee	Position	Company	Industry sector
Interviewee 1	Development Engineer	Company A	Automotive Sector
Interviewee 2	Development Engineer	Company B	Plastics Processing Industry
Interviewee 3	Senior Business Development Manager	Company C	Software Solutions for AM
Interviewee 4	Head of 3DP	Company D	Mechanical Engineering / 3DP Service Provider
Interviewee 5	AM Consultant	Company E	3D Printer Manufacturer

4 Findings

4.1 Use and Evaluation of 3D Printing in Selected Companies

All interviewees agree on the fact that AM is mostly used in prototyping or the production of operating tools. Some serial applications can be observed in specific industries such as medicine, aerospace and automotive. Regarding changes in production, it can generally be observed that mainly the development process has changed instead of the actual production. The development of products is quicker, as well as more flexible.

The interviewees see various advantages which can be associated with 3DP. One of the most frequently named aspects was the time reduction. Moreover, it is possible to react quicker since it is easy to print the components needed. However, there are also some limitations according to the interviewees. Firstly, the production process is slower. Moreover, the standardization of the 3DP process is not yet mature.

Regarding the disruptive potential, the interviewees are all in agreement. All of them see that there is a disruptive potential to 3DP and that the technology will disrupt the market to some extent. However, given the disadvantages, the application of AM will be rather complementary than substitutive.

4.2 Impact of 3D Printing on Supply Chains in Selected Companies

Since AM is mostly used for prototyping in the interviewees' companies, most of the impact factors identified from the interviewees are associated with the future potential. Nonetheless, the interviewees also described actual impacts they have been able to observe in their supply chains. For instance, Interviewees 1, 3 and 4 claimed that 3DP helped to bridge delivery times. Through 3DP, the required components could be printed directly which resulted in shorter delays.

AM poses the possibility in the given companies to reduce the dependencies from their suppliers since they can print the components they need in case of delays. Despite the fact that critical situations such as supply chain disruptions have already demonstrated that 3DP can decrease dependence on suppliers, Interviewees 2, 3 and 5 see no possibility for this outcome. Nonetheless, all interviewees see opportunities to improve customer experiences. Especially customers can be offered more performance.

Regarding the impact factors, all interviewees see a high impact of AM on mass customization since 3DP offers the possibility of producing a large number of parts with a high degree of individualization. Mass customization is mainly relevant in industries in which the products are directly addressed to customers, such as medicine, eyewear, or sports. The participants elaborate that AM has great potential to enable resource efficiencies. These effects have already been realized in the given companies. Reasons for this include the possibility of recycling and thus reusing printing materials. All interviewees reportedly see the effects on the decentralization of production in the future. Nevertheless, all interviewees see great potential and associated advantages through the increasing decentralization that will take place in the future. So far, almost no participant has noticed any changes in the complexity of supply chains. Some of the participants see a strong potential to reduce the complexity of the supply chains in the future. However, some have the opinion, that supply chains will become more flexible in the future but by no means less complex. In rationalization of inventory and logistics, all interviewees sense a very large potential for optimization and cost savings, but mostly for future applications. Interviewee 4 has already been able to achieve advantages for one of his customers in the field of logistics through the lightweight construction of heavy objects, which can now be transported more easily. All interviewees agree that 3DP is already well represented in prototyping and product design. One aspect is that more individual design can be created more easily. The costs for product development greatly reduced by AM. Some of the interviewees have concerns regarding the legal and security issues posed by 3DP in production. It can be seen as a clear objection that needs to be addressed before mass implementation of AM.

Although the interviewees reported many positive impacts, they see a lot of effort associated with the implementation of AM in supply chains. One of the reasons is the complexity of the technology. Therefore, companies should ask themselves whether they should operate 3DP in-house or whether they would prefer to outsource it. Regarding the supply chain managers, the interviewees see a compelling expansion of skills. They must have know-how to be able to efficiently manage supply chains with AM.

Regarding the future of 3DP all interviewees see a lot of potential for 3DP. They assume that there will be continuous developments of the technology. With a faster and more efficient production process, the technology would be used more often. In general, the interviewees see it as likely that 3DP will be an essential component in manufacturing in the future. Thus, all interviewees recommend investing in 3DP and using it for the production in the future. Particularly high potential can be seen in aerospace, medicine, semiconductors and the chemical industry.

5 Discussion

This paper investigates the research question: What are the current and future impacts of 3D printing on supply chains? It can be concluded that there are impacts on supply chains and that there have been changes determined in the selected companies. However, these changes are mostly in the fields of prototyping and bridging critical situations. There have not yet been any drastic changes in the normal supply chains. At least not in the companies selected for this paper. Nonetheless, one can see that there is a great

potential for changes in the companies' supply chains, especially because there will be an increasing number of use cases over time. 3DP has proven to be an optimal solution especially in critical times. Nevertheless, 3DP still has a long way to go before it can be widely applied in the production of end products. It is also debated whether the share of AM in the global production market is too small to have vast impacts on supply chains.

Moreover, it can be questioned whether the impact will actually be as extreme as portrayed in the proposed supply chain model. One reason for this is that the technology is predominantly seen as a complementary technology and will therefore only be used in production situations that fit 3DP. These production situations consist primarily of small batch sizes with a high degree of individualization.

Furthermore, it is made clear that 3DP will advance digital production. There are significantly more opportunities for on-demand production in contrast to conventional manufacturing, which encourages companies to avoid overproduction. Moreover, AM offers great potential for decentralizing manufacturing, which is a significant contribution to sustainability. The reason for his is that the need for global transportation is drastically reduced in a distributed manufacturing setup. If AM can ultimately be used in large batch sizes, the impact on supply chains will increase significantly.

It can be summarized that impacts have already been identified in mass customization, resource efficiency, rationalization of inventory and logistics as well as prototyping and product design. Mass customization is mostly relevant in specific customer-oriented industries. Resource efficiency has had impacts in all companies. The rationalization of inventory and logistics was mostly reported by one company. Prototyping and product design is an aspect that all interviewees can agree on and see the 3DP technology as a clear substitute to conventional methods. In addition, there is a significant increase in customer satisfaction and reduction of supplier dependencies due to the possibility to overcome supply chain disruptions and supply chain bottlenecks. Future impact is seen overwhelmingly by most interviewees in all impact areas. Nonetheless, it should be taken into consideration that there are companies that operate entirely with 3DP. It is possible that the results of these companies could differ. Table 2 summarizes the results of the present paper.

Table 2. Current and future impacts of 3D printing on supply chains

Impact factor	Current impact	Future impact
Mass Customization	Yes	Yes
Resource Efficiency	Yes	Yes
Decentralization of Production	No	Yes
Complexity of Supply Chains	No	Yes and No
Rationalization of Inventory and Logistics	Yes and No	Yes
Prototyping and Product Design	Yes	Yes
Reduction of Dependencies	Yes and No	Yes and No
Customer Experience	Yes	Yes

As a part of the results of this paper, recommendations for action will be provided. The reason for this, as discussed in the introduction, is that the disruptive potential of 3DP can lead to vast transformations in companies. Therefore, recommendations for action will be derived from the results of this study.

Firstly, it is of high importance to clarify which companies should use 3DP in the future. The results of this paper suggest that the potential for 3DP is especially high in aerospace, medical, logistics, automotive, railway, semiconductors and the chemical industry. Nevertheless, the findings show recommendations for all companies to invest in 3DP, as it can lead to optimization potential in companies and bridge disruptions in supply chains. In general, it is recommended in production with small series and a high degree of individualization.

The second aspect of the recommendation for action is concerned with the implementation of AM. Based on the results of this study, it can be deduced that the introduction of 3DP is associated with a high level of effort. It is therefore worth considering outsourcing the 3DP process to service providers. In conclusion, it is critical for companies to acquire knowledge about the technology and its impact. 3DP should initially and most likely in the future be seen as a complementary technology, supplementing conventional methods where it is beneficial. Companies that integrate AM may be more responsive and independent due to the high flexibility in their supply chains.

6 Conclusion

This paper is able to identify impact areas of AM on supply chains as well as current and future changes of supply chains. From this, recommendations for action could be derived regarding the future use of 3DP in different industries. The increasing relevance of 3DP in the corporate world has been highlighted. This underlined the importance of this study to investigate the changes of supply chains and to give recommendations for action for companies using 3DP or striving to implement 3DP in their supply chains.

By conducting semi-structured interviews with five selected companies, the use of 3DP in different industry branches, as well as the impacts on their supply chains were examined. The analysis has shown that 3DP is mostly used in prototyping. Hence the impacts on supply chains are still small but nonetheless all interviewees have experienced impacts on the supply chains in their companies due to higher flexibility and shorter lead times. All interviewees see high potential for the further development of the technology. As the objective of this study was to identify current and future impacts of 3DP on supply chains, current impacts could be identified in customer experience, reduction of dependencies, mass customization, resource efficiency, rationalization of logistics, and prototyping and product design. In the future, the impacts on supply chains are going to increase steadily due to a gradually rising number of applications. Especially contributions to sustainability regarding the reduction of the carbon footprint and decreased material wastage can be seen in future applications of AM in supply chains. It is apparent that 3DP can be recommended to all companies due to the high number of benefits, especially on the supply chains.

To ensure more expressive results, more interviews would have to be conducted. Since this study determined that for the selected companies, 3DP is still in early adoption and mostly applied in prototyping as well as in critical situations in their supply

chains, future work should assess this topic in a further manner since it is of ongoing importance. It would be best to enlarge the number of participants and assess more industries and companies by applying quantitative research methods. This can help in giving recommendations for action for specific industries. Moreover, it would be recommended to examine companies that exclusively use 3DP in their production since they have possibly experienced greater impacts and changes in their supply chains.

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