Impacts of Additive Manufacturing on Supply Chains: An Empirical Investigation

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Abstract. Over the last decade, Additive Manufacturing has received an increased attention as many manufacturing companies have increasingly adopted new technologies to capture new opportunities. This research identifies the impacts of Additive Manufacturing (AM) on the supply chain when compared to the case of conventional manufacturing. Through an empirical investigation conducted with 17 multinational companies in the manufacturing sector, the impacts of AM are analysed by focusing on post-processing operations, lead times, cost implications and the use of the make-to-order & make-to-stock strategies. The empirical investigation reveals two major benefits of AM, namely: the ability to produce complex parts and the reduction of inventory levels. However, the empirical results were mixed for some other impacts of AM. In fact, although many experts agreed on the general benefits of AM, a significant number did not see much difference from the conventional methods. We also provide empirical evidence that, under AM, lead-times do not reduce as opposite to what is reported in the literature, which might be due to the extra time required for quality checks and post-processing.

Keywords: Additive manufacturing, supply chain, conventional manufacturing, empirical investigation.

1 Introduction

Nowadays, the global supply chain continues to be disrupted by new technologies, especially in the manufacturing sector and logistics operations [1]. Three dimensions printing using Additive Manufacturing (AM) is one of the technologies that is expected to revolutionize how things are manufactured [1]. AM is commonly defined as the process of joining different materials to come up with a 3D model, which is usually done layer upon layer [2]. The Additive manufacturing process starts with the development of a 3D model by the use of computer-Aided Design software [2]. The 3D model contains all the specifications and essential details of the product. The creation of a 3D project requires some basic essential ingredients including feed materials, the digital model, and the 3D printer as shown in Figure 1.

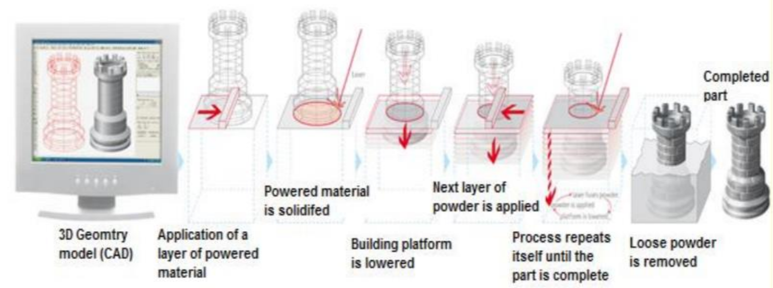

Fig. 1. Additive manufacturing process. Source [7].

The academic literature shows that, by using AM, many companies have experienced increased agility and flexibility, which allows for better use of resources and materials, which results in low cost of production [3]. Besides, manufacturers of customized products experience high flexibility with competitive production costs and high added value. It has also been linked to other benefits such as the reduction of carbon emissions due to the reduction of transportation activities, which is a key issue, being advocated by the United Nations in a bid to protect and conserve the environment [4]. However, AM is also linked to some drawbacks, including the requirements for post-processing and slow build rates. The popularization and relevance of additive manufacturing in modern companies have increased the academic interest to understand its implications and benefits on the supply chain [4]. However, it should be noted that most of the existing empirical studies have only focused on few levels and processes of the supply chain, mainly the production and inventory management. To bridge this gap in the literature constitutes one of the objectives of our paper.

This work aims to empirically investigate the impacts of AM on supply chains. This will contribute to the existing literature by extending the scope of the analysis to include the impacts on all levels and processes of the supply chain, from the procurement to the relationship with customers, including the design and prototyping stage. Note also that our empirical investigation is conducted with a good sample of multinational companies having an experience with AM. Also, the research will be help to answer more questions in supply chain such as the contexts where AM is more applicable in the supply chain, which is important for the organizations' decision making.

This study is organized as follows. After presenting the context and objectives of the paper in this introductory section, we present in Section 2 a theoretical analysis that provides a broader area of knowledge on the impact of AM on the supply chain. Section 3 is dedicated to the empirical investigation, which discusses the research methodology and the empirical findings of the study. We close the paper in Section 4 with some conclusions and avenues for future research.

2 Theoretical analysis

The AM technologies have a very disruptive impact on the global supply chain. In this section, based on our review of the literature, we identify the impacts of AM on four dimensions of the supply chain, namely: the procurement, the production and operations, the transportation and inventory, and the manufacturer/customer relationship.

2.1. Impact on procurement

In any supply chain, a strong relationship between the manufacturer and the suppliers of raw materials is very essential. In AM, unavailability of raw materials might result in long unproductivity given that suppliers of the AM raw materials are very limited [5]. Therefore, the manufacturers have to carefully select and establish strong relationships with the suppliers unlike in conventional manufacturing where there are a higher number of suppliers of raw materials. The AM technology in the supply chain helps to lower the supply risk. This is because 3DP allows a product to be produced using a single raw material or a mixture of different materials, which eliminates the need for the manufacturer to source costly components and sub-assemblies.

2.2. Impact on production and operations

Unlike conventional production, which focuses on mass production, the AM technology could drive the transition to mass customization tailoring the products to each of the customer's requirements [5]. This means that customers are able to be involved in the design and production activities, which can change priorities of cost and profit management and hence making the supply chain more agile and flexible according to the different market changes. Given that the AM technology is highly flexible, the technology is able to produce a wide range of different outputs easily, quickly and cheaply. Therefore, the AM technology plays a very essential role in the creation of innovative processes for the production and testing of prototypes or updating product designs [5]. The technology is also applicable in direct product manufacturing especially for products with the need for customizability and complexity but with low production volumes [8]. Therefore, due to the additive nature of the technology, product designers and manufacturers are not tied to traditional constraints such as design for manufacturing. Instead, the technology allows many products to be redesigned. Finally, AM is strongly correlated with the product complexity. In fact, the more complex the product is in terms of shape and design features, the more beneficial AM will be over conventional manufacturing methods and the more cost saving can be achieved. Under the conventional manufacturing methods, the production process time and cost will increase with the design complexity. Conversely, production time and costs under AM should not be much impacted by the level of design complexity neither the flexibility of production.

2.3. Impacts on transportation and inventory

The movement of different products across the globe is being replaced by the movement of the 3D files while the physical inventories of the finished products are being replaced by digital inventories. By using the 3DP, the raw materials are used in the final manufacturing of the product and by producing on-demand, which means that there are fewer finished goods to be stocked or transported. This allows for warehousing and logistics to be rationalized as well as reduced logistical costs and positive environmental effects [7]. The inventory of the raw materials used is also cheaper and safer compared to conventional manufacturing. Due to the precision of the technology, AM products should be lighter and potentially more compact than an equivalent part conventionally manufactured, which leads to a reduction of the transportation and inventory holding costs. It is also worth pointing out that in relation with the complexity of products, integrating the parts of a product in a single piece could also reduce the need for the upstream transportation to source numerous parts. This results in reduced logistics cost, simplifying the management of logistical flows and positive environmental impacts as well as the reduction of disruptions along the supply chain. Integrating the parts in a single piece could also decrease the raw materials and WIP inventories, which means a potential for reduced holding costs.
Through reshoring, AM could play a key role in reducing demand for the global transportation whereby the physical flow will be replaced with the transfer of digital files [9]. Also, as noted above, inventories could then be affected due to the increased use of on-demand production possibilities of AM and this will have great and long-lasting impacts on the supply chains as well as the supply chain management.

2.4. Impact on manufacturer/Customer relationship

The AM shifts the production of goods closer to the final consumer and enhances the build-to-order approaches that have a positive impact on the manufacturer-customer relationship [7]. By using the AM, customers become part of the manufacturing processes whereby they can design and transfer ready-to-print files to the manufacturer and hence become a core creator, which promotes faster turnover [10]. According to Chekurov et al. [5], the technology has increased the role of the customer in the process as they have been given control over the design and production in collaboration with the manufacturer a relationship referred to as prosumers [5]. Overall, AM transforms the way the final consumer is reached more efficiently and effectively, further strengthening the customer-manufacturer relationship.

To validate some of the findings of the theoretical analysis for the impacts of AM on the supply chain, an empirical investigation should be conducted with a sample of manufacturing companies. The following section presents the research methodology used to provide empirical evidence of some impacts and limitations of AM.

3 Empirical investigation

The main objectives of the empirical investigations are:
- To empirically validate or refute some impacts of AM that are identified in the theoretical analysis**;**
- To focus on the main interrogations and unclarities related to AM

3.1. Target audience and research participants

Given that the findings of the research will depend on the composition of the participants to the study, a great care was given to the selection of the target audience. The first step aimed to identify the target audience involving potential experts from different industries with expertise in AM and supply chain management. We have obtained their contacts from different sources, mainly the University alumni database, and the LinkedIn network. By analyzing their credentials, we have assessed whether they were sufficiently qualified to take part in the survey as experts. An invitation letter was then sent to the potential participants including a short explanation of the aim of the study. Finally, a panel of experts from 17 multinational companies agreed to take part in the study. The list of companies includes Safran, Alstom, Michelin, Mercedes-Benz, Siemens, Ford, Schlumberger, BMW, Total, AM Polymers GmbH, and American Additive Manufacturing.

3.2. Research process

First, the study used a critical literature review to investigate different manufacturing companies and suppliers that have used the 3DP technology. The literature review was important as it helped to identify the present knowledge research gaps in this area of study. The study's empirical investigation began from the theoretical foundation and then moved into the main research data whereby both qualitative and quantitative data were collected from different case studies through questionnaires. The questionnaire sent to the participants is composed of 61 questions, which were divided into 8 subsections whereby the questions are sought to capture and address: (1) Preliminary information of the company; (2) Workforce of the company; (3) Pros & Cons of AM; (4) Post processing operations; (5) Quality; (6) Lead Time & operations duration; (7) Cost impacts; (8) Make To Order (MTO) versus Make To Stock (MTS) and low volumes versus high volumes.

4 Findings and Discussions

4.1. Context of the use of AM

We first analyzed the type of materials (plastic and metal) used by the companies in AM manufacturing. The empirical research shows that the majority (84.62%) of the manufacturing companies use both plastics and metals. In addition, we sought to determine whether for the companies, AM production is done in-house or through outsourcing. The empirical results show that 41% of the companies use both the in-house and outsourcing, 18% of the companies only outsource the AM products while 41% uses in-house production.

4.2. Pros and cons of the use of AM

The companies were asked about the benefits of AM in their supply chain. The confirmed benefits and the percentage of companies, reported in Figure 2, are: Produce complex parts (76%), Cost beneficial on low volumes (82%), Parts consolidation (52%), and Great Design & Prototyping (70%). The refuted benefits include; Reduced number of suppliers (17%) and a reduced need for transportation (35%) and less material waste (50%). These findings are in line with the findings by Chan et al. [10] who state that 3DP enhances the capability to produce components that are more complex at a low cost and allows for a great design and prototyping.

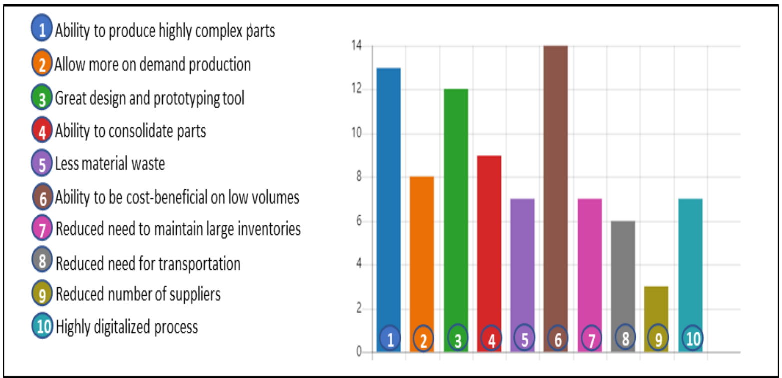

Fig. 2. Benefits of AM

This research is also sought to identify the disadvantages of using AM from the perspectives of the considered companies, as shown in the Figure 3. The main cons validated by the empirical investigation include: the important capital expenditures required to develop AM, confirmed by 47% of the companies, the extended quality checks, the need for a specific workforce and some thermal or structural issues such as the risk for distortions and stresses during the cooling phase, which were confirmed by 47% of the companies as well. The less validated cons include: the risk for supply shortage (17%) and the long manufacturing time on large volumes (17%).

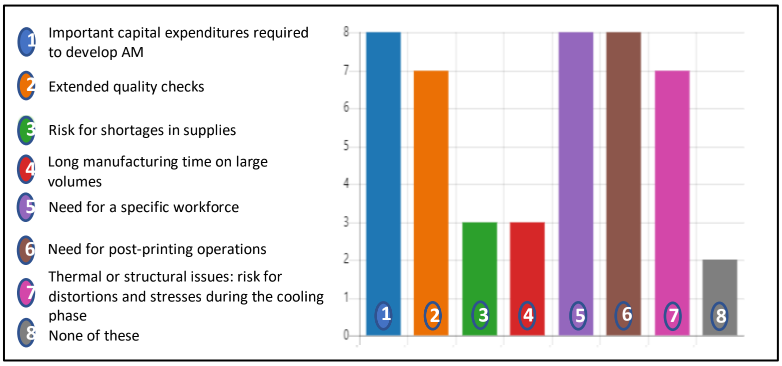

Fig. 3. Cons of AM

4.3. Post-processing operations

The companies were also asked about the post-processing operations as impacted by AM. The results show that 70% of the companies need to perform post-processing operations and out of the 70%, 66% outsource some post-processing operations, which allow them to focus on the core competencies. These results are in line with some of the reasons why organizations use the dual sourcing whereby organizations achieve a competitive advantage when they combine their core competencies and abilities with those of their customers, suppliers and other external resources [11]. As shown in Figure 4, the empirical results also reveal that the duration of the post-processing phase greatly depends on the product while 62% reported that production when using AM was below 40% of production time. This finding supports the suggestions by Chan et al. [10] who stated that 3D printing provides an opportunity for manufactures to reduce lead-time production.

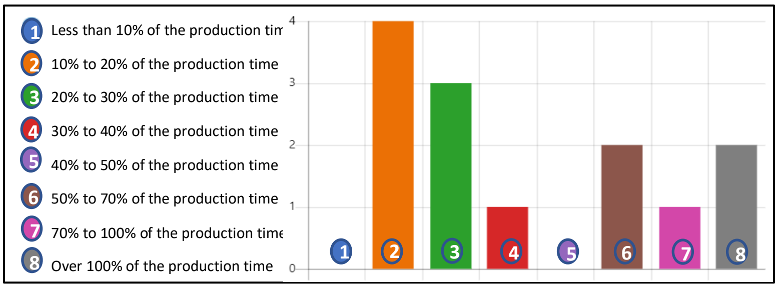

Fig. 4. Post-processing operations

4.4. Lead Times of different Phases

Here we compare the lead times of different phases in AM to those of the conventional manufacturing method. In general, 70% of the companies stated that AM reduced overall product development time (entire process) while 30% stated that there was no change. However, in the design phase, the majority of the experts 41% stated that it remained the same, 29% said that it was longer while 29% stated that it was shorter.

For prototyping, 92% of the experts stated that it was shorter. This supports the research by Chan et al. [10] who stated that AM allows for rapid prototyping by the use of CAD.

The majority of the respondents, 46%, stated that the production time using AM was shorter than that of the conventional production, which is in line with the findings of Kunovjanek & Reiner [6] which shows that 3DP technology plays a crucial role in reducing the production lead-time due to less assembly times required and less delivery times between processes.

For post-processing, 30% of the respondents stated that it was longer compared to conventional manufacturing while 70% stated that it was similar. For the control phase, 70% stated that it was similar while 30% stated that it was longer. This might be due to the fact that extra time is needed for quality checks and post-processing.

4.5. Cost implications

In terms of cost implications, the empirical results show that 62% of the respondents stated that production cost is significantly reduced by 30% or more when using AM. This agrees with Kunovjanek et al. [6] who stated that production lead times when using 3DP is reduced significantly which contributes to production costs but disagrees with Sirichakwal & Conner, [12], who stated that the 3DP technology may not have an edge over the conventional technology in terms of the cost of production.

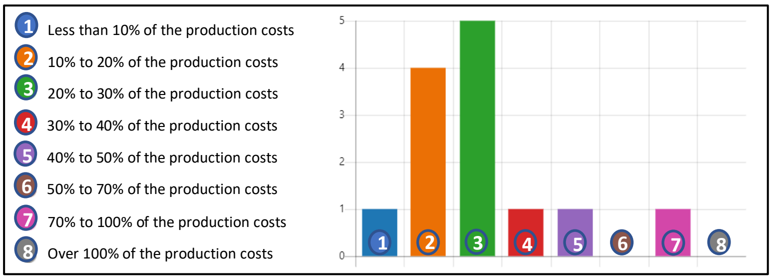

Fig. 5. Cost implications

The results also show that 53% of the experts think that AM has significant cost implications on procurement, 59% on the design phase, 71% think it has cost implications on inventory. This agrees with the findings by Gao et al., [13] who stated that AM offers quick customized solutions and a great opportunity for MTO, which reduces the cost on inventory and procurement. In the design phase and production, Chan et al. [10] note that AM reduces the costs by improving the efficiency as well as shortening the development time. However, the majority of the respondents (59%) did confirm this, which concurs with the findings by Chan et al. [10] who states that cost of production when using AM is also lower because it takes place with minimum labor and labor cost. However, this depends on the cost incurred in different phases of the supply chain whereby some design and development phases are relatively costly compared to the production cost.

4.6. MTO vs. MTS and Low Volumes vs. High Volumes

The empirical results show that 53% of the respondents stated that they were using the MTO strategy with AM, 20% are using MTS while 27% are using both strategies.

54% of the respondents agreed that AM is relevant in an MTS vs MTO strategy while 46% disagreed. These mixed results are in line with the findings by Nickels [14] who stated that in the future, manufacturers will be able to produce AM spare parts on demand especially in decentralized locations whereby the order penetration will be through MTO. On the other hand, even though Ryan et al. [15] questions the usability of AM in MTS due to the lack of customization, Olhager [16] states that with long production times, MTS becomes more appropriate than MTO as it can help to have products ready to ship.

The majority of the respondents (62%) disagreed that AM is only interesting on low volumes while only 38% agreed. These findings however contradict the suggestions by Potstada & Zybura [17] who states that AM in MTS is most appropriate for small scale products especially with the current printers and [14] who states that AM in MTO is mainly applicable for low volumes by use of specialized equipment.

5 Conclusion

This research has theoretically and empirically identified some of the most significant impacts of additive manufacturing on the supply chain, including the procurement, the production & operations, the transportation & inventory and the manufacturer-to-manufacturer relationship. The study significantly contributes to the limited literature on the link between AM and all supply chain processes and it is a response to the existing calls for further research. The review of the literature reveals that there is a great potential for AM, which is expected to reduce the production time, reduce costs, and allow for easier customization. However, the majority of the studies dealing with the impacts of AM on supply chains have ignored the fact that the impacts can be different at different levels and processes of the supply chain. Therefore, we have conducted an empirical investigation with a panel of experts in major manufacturing companies to give their insights on how AM impacts different levels/processes of the supply chain. The empirical results have revealed two major impacts of AM: the ability to produce complex parts and the reduction of the inventory levels.

The research has generated important valuable insights to the AM research. However, it should be noted that the results have also portrayed many mixed results with regard to the cost implications, the post-processing operations, and the lead times. This, therefore, leads to the suggestion that AM has only enabled the transition but the conventional manufacturing will not be entirely phased out. AM should in the meantime complement conventional manufacturing. However, the empirical investigation has been based on a limited sample size, which may limit the generalization of the findings. Hence, it is recommended that more research should be conducted using larger empirical samples and other methods such as simulation models or relativity analysis and regression to better validate the current study's findings.

It is worth pointing out that the findings of the empirical investigation provide evidence of the impact of AM on the supply chain performance. The companies' sample considered in the empirical investigation in this paper is rich enough (multinational companies with different sizes and proposing different types of products) to be representative for general contexts. However, it is obvious that the generalisability of the findings cannot be confirmed due to the limited size of the sample of considered companies, which may represent a limitation of this research work. Hence, extending the analysis by considering a bigger sample of companies would be an interesting avenue for further research contributing to the generalisability of this article's findings.

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