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The Role of Additive Manufacturing in Supply Chain Management

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Abstract
Nowadays, it is necessary to develop a conceptual framework for analysing the relationship between the implementation of Additive Manufacturing (AM) and Supply Chain Management (SCM). In this context, a gap in the research has been observed in the new approach to designing the importance of AM in SCM. The main contribution of this paper, therefore, is a new framework to formulate the role in adopting AM in SCM. The research methodology is based on detailed literature studies of AM in relation to the SCM process within a manufacturing company, as well on a case study, namely the COWAN GmbH manufacturing company who specialise in producing homewares for motorhome enthusiasts. As highlighted in the state-of-the-art analysis, no work, currently available, supports all the features presented.

Keywords
Additive Manufacturing, 3D printing, Supply Chain Management.

Introduction

In the modern world, one of the most important challenges for the success of manufacturers, according to the concept Industry 4.0, is to improve the efficiency and flexibility of production processes. Customers are looking for innovative, personalised and high-quality products at attractive prices. In addition, the economic lifecycle of products is constantly shortening as products become ever more diversified and individualised. One way to meet all these requirements is to implement Additive Manufacturing (AM) in manufacturing enterprises. AM technologies are used in order to transform a three-dimensional (3D) digital model into a 3D physical object, layer-by-layer, through the deposition of successive material (Sames et al., 2016). AM can, therefore, be defined as a set of methods to combine materials together, in order to produce physical, three-dimensional objects based on their computer model. Various methods are used here (Tofail et al., 2017), (Bourell et al., 2017) to apply such materials, layer-by-layer and bond powdered or liquid materials together, such as metals, ceramics, polymers, composites, hybrid materials, or materials classified as plastics gradient. Examples of AM methods are e.g.: Binder Jetting (BJ), Directed Energy Deposition (DED), Materials Extrusion (ME), Materials Jetting (MJ), Powder Bed Fusion (PBF), Sheet Lamination (SL), Vat Photo-polymerisation (VP) (Fiał& Pieknik, 2020a). AM is associated with the relatively low emission of gases and dust (Karwasz & Osiński, 2020).

Even though AM was invented to produce prototypes quickly, the technology has the ability to reduce design and manufacturing constraints in development products with complex geometries and relatively small sizes (Kaczorowska & Jakubowski, 2020), Kuczko et al., 2021). Additionally, using this technology can reduce the weight of components, including reducing the number of parts which, ultimately, have a bearing on cracking and fatigue levels, due to residual stresses and micro-structural features (Citarella & Giannella, 2021). The properties of the manufactured elements are determined by the type of material used and the direction of printing in the AM technology ap-

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plied (Dębski et al., 2021). AM is mostly used in the aerospace, automotive, electronics, medical, architectural, construction, textile, energy and food industries (Haghnegahdar et al., 2022), (Fiał & Pieknik, 2020b). Whole parts can be produced with Additive Manufacturing or just some structural elements with hybrid manufacturing (Budzik et al. 2020). AM techniques are also used for the production of high-performance, functional coatings (Kumar & Menezes, 2021).

AM is one of the solutions driving the transition to Industry 4.0. This transformation reconfigures the supply chain to achieve the circular economy (CE) along with improved resource efficiency (Hettiarachichi et al., 2022).

The great potential of AM is the possibility of using it to reconfigure traditional supply chains and the possibility of reducing many of the existing limitations in Supply Chain Management (SCM) – this can be also applied to retailers (Arbabian, 2022). SCM is a way to secure the performance and competitiveness of enterprises and to react quickly, effectively and efficiently to changes in the market. SCM could be referred to as a form of the implementation of Industry 4.0 due to real-time data exchange across the supply chain and between products, customers, and production facilities enabled by the Internet of Things (Birkel & Muller, 2021). According to the statement, that companies need to be integrated into the concept of Industry 4.0 across the supply chain (Moeuf et al., 2018), this article attempts to develop a conceptual framework for analysing the relationships between the implementation of AM and SCM. In summary, this paper addresses the following research questions (RQ):

RQ1: What factors, the adoption of which, AM is associated with, have impacted on SCM?

RQ2: How can the process of SCM be improved with the implementation of AM in manufacturing?

The main contribution of this paper is a new model that defines the relationships between the implementation of AM and SCM. The proposed new framework has been partly implemented in the manufacturing company COWAN GmbH, to illustrate that the implementation of AM can improve the Supply Chain Management process.

The remainder of this paper is organised as follows. Section 2 describes the materials and methods. Section 3 describes the theoretical background of the adoption of AM and its role in SCM. Section 4 explains the innovative approach to defining the relationships between the implementation of AM and SCM. Section 5 illustrates the new framework through a case study, followed by a discussion of the key findings.

Materials and methods

The first step of the research is an analysis of the literature regarding the adoption of AM which focusses on its effects on the partners involved in SCM. In that context, SCM is treated as the management of relationships with suppliers and customers to produce enhanced value at a lower cost to the supply chain (Jüttner et al., 2010). Current professional literature has, therefore, been analysed, highlighting the main factors, with which AM adoption is associated. In researching the literature, a research gap was identified in the context of the impact on SCM of the implementation of AM, thus addressing RQ1. The second research question (RQ2) was investigated and conceptualised in the form of the literature already extant on the subject, in order to define the new procedure for improving the process of SCM with the implementation of AM in manufacturing. Next, data received from the COWAN GmbH manufacturing company was used, additionally, in order to provide more robustness to the research.

Research results: a new approach to designing the role of AM to SCM

This chapter provides an answer to RQ1 and RQ2. Article (Arbabian & Wagner, 2020) examines the impact of AM on the supply chain, consisting of a producer and a retailer that serves customer demand. 3D printers can be installed at the manufacturer as well as at the retailer in the supply chain, which allows demand to be responded to more effectively. One example of the installation of machines at a manufacturer's premises, is the use, by BMW, of 3D printing technology for the production of spare parts for cars. In this case, the manufacturer invested in the purchase of 3D printers, operating at dealerships and also developed 3D designs. This allowed traditional production lines, that were used exclusively for the production of spare parts, to be closed down. Accordingly, the company was able to switch to a custom production policy. As an example of installing 3D printers at a retailer, UPS stores can be mentioned, where, if links in a supply chain are missing, you can ask UPS to 3D print products. Both cases were analysed according to the Stackelberg model which defines the economic and competitive conditions under which each company adopted 3D printing and showed that, in any scenario, both companies can generate more profits than without 3D printing.

In article (Dongmin et al., 2021) a new, closed-loop supply chain model with additive technology hubs was proposed. This supply chain combines the advantages of additive and conventional manufacturing systems. The research was performed to facilitate decision making in the use of an incremental manufacturing method. As part of the research, a closed supply chain with an additive technology concentrator (CLSCAM) was designed. It then developed a CLSCAM lifecycle sustainability assessment model (cost, environment and time) and a parts consolidation method that maximises sustainability rates. Due to the fact that the problem of consolidating parts of a complicated product is NP-hard, a genetic algorithm was used as a solution method. An experimental analysis was also carried out to validate the proposed model by applying it to the real world. Experimental analysis showed that all sustainability metrics are improved when consolidation options for parts and additive manufacturing concentrators are available. In addition, it was found that most sustainability indicators improve with increasing demand. The results also indicated that while using supply chains with AM, manufacturers should focus on improving the cost of the pre-production stage. According to the sensitivity analysis, the impact of the consolidation of parts on the sustainability of the supply chain increases, as the efficiency of raw material consumption improves.

Another article (Yilmaz, 2020) describes the problem of integrated vehicle tasks and schedules in a two-stage supply chain where parts are processed on AM machines and then distributed to customers. A problem optimisation model was developed to shorten the implementation time of the project. Since the problem in question belonged to the non-deterministic polynomial class, the best-fit approach and several selection rules were developed to solve this problem. Each of the selection rules is a different algorithm created, taking into account the structural property of the problem. A comprehensive experimental study was carried out, randomly, taking into account real production data. According to the calculation results, the algorithm for selecting the best-fit based on utilisation of the bandwidth, provides the best marketspan. The reason was that the use of production capacity, with an optimised supply chain, enables a large number of tasks to be completed in a short time.

According to article (Dircksen & Feldmann, 2020) AM is associated with the possibility of increasing revenues and saving costs, as well as reducing the impact of production on the stability of the natural environment. Nevertheless, deciding between local production, with Additive Manufacturing and the global distribution of goods, requires a holistic analysis. Therefore, a decision model was developed to assess the impact of AM on greenhouse gas emissions, distribution costs and lead times in global supply chains. This was done by formulating research questions as to how to quantify the economic and environmental impacts of different scenarios early in the planning of the global supply chain, in a holistic decision model and what is the main impact of AM on green sustainability at different stages in the lifecycle of a product, produced from AM. A case study of distribution processes, from Brazil to Germany compared to additive production in Germany made it possible to determine the usefulness of the model. Moreover, the model is highly flexible as the methodology allows several factors to be estimated.

In article (Nuñez et al., 2020) a system dynamics model was developed, the main goal of which was the visualisation of a supply chain where this includes AM. The model was in the form of a causal diagram in thirteen variables, related to the supply chain, ordered in two, feedback cycles and a data flow diagram, hinged on the three-essential links of the supply chain and the display of relations: supplier–focal manufacturer–distribution network. The dynamic behaviour of the variables that determines the chain management was analysed, showing reduction times in production. This was especially true for products requiring greater complexity and detail, as well as reducing the inventory of expensive, raw materials. The model was validated through the evaluation of extreme conditions and sensitivity analysis.

Article (Meier, 2020) discusses possible scenarios of SCM with AM. Decision support for management that is responsible for long-term strategic decisions has been suggested here too. Based on the assumptions of the stages of development of Additive Manufacturing, it introduced scenarios systematically, using the standard SCOR model nomenclature. It was found that along with the spread of AM, new competitive goods may arise and there would be the possibility of the customisation of products by the client. Furthermore, new SCM models can be used to respond quickly and flexibly to customer requests.

The study (Sharma et al., 2020) found that the combination of traditional SCM with sustainable AM improves environmental performance and the green image of industries. Sustainable SCM indicators were identified through a survey of the literature. Data was collected by surveying industry. The indicators were positioned using the analytical hierarchy process according to which, procurement cost was recognised as a key indicator in implementing sustainable SCM practices for AM.

The paper (Mastos et al., 2021) shows that redesigning supply chains, using Industry 4.0 technologies, can enable closed-loop SCM. A waste-to-energy solution for Industry 4.0 has been developed. The proposed solution provides process monitoring, information transparency and decision support, resulting in improved economic efficiency. There are benefits from combining the solution thus developed with the six dimensions of the ReSOLVE model's circular economy, such as regeneration, sharing, optimisation, looping, virtualisation and exchange. Additionally, application of the solution in three companies proved this empirically.

Article (Esmaeilian et al., 2020) includes a review and evaluation of Industry 4.0 research for the development of sustainable SCM. The possibilities of Industry 4.0 in three groups were found here: energy management, using the Internet of Things in smart factories, intelligent logistics and transport and smart business models.

By analysing the literature on the subject, it was possible to identify the main areas in which the role of AM in SCM is focussed, dictated by the digital revolution of industry. Data obtained on the basis of literature analysis was collected and summarised in Table 1.

Table 1
Collected and analysed data from the literature

Aspect of AM in SCM	Profit for SCM	Research method	Impact on SCM (yes/no)	Ref.
installation of 3D printers and the development of 3D projects by the producer and retailer	using 3D printers generates best profit outcomes for the manufacturer	analysis according to the Stackelberg model	yes	(Arbabian & Wagner, 2020)
closed-loop supply chain model with additive technology hubs	sustainability metrics improve when parts consolidation options and AM concentrators are available	genetic algorithm and experimental analysis	yes	(Dongmin et al., 2021)
two-stage supply chain where parts are processed on AM machines and then distributed to customers	using production capacity with an optimised supply chain enables a large number of tasks to be completed in a short time	the best-fit approach and several selection rules	yes	(Yilmaz, 2020)
supply chain with AM	AM is associated with the possibility of increasing revenues, saving costs and reducing the impact of production on the stability of the natural environment	holistic decision model, which allows variable factors to be estimated; case study	yes	(Dircksen & Feldmann, 2020)
supply chain with AM	where the supply chain includes AM, production times can be reduced	system dynamics model in the form of a causal diagram in thirteen variables related to the supply chain, evaluation of extreme conditions and sensitivity analysis	yes	(Nuñez et al., 2020)
supply chain with AM	new SCM models with AM can be used to respond quickly and flexibly to customer requests	systematically introduced scenarios using the standard SCOR model nomenclature	yes	(Meier, 2020)
the combination of traditional SCM with sustainability	SCM for AM improves environmental performance	literature survey	yes	(Sharma et al., 2020)
the combination of three dimensions of SCM in implementing AM	The ability to monitor the effects of the implementation of AM in SCM manufacturing	literature review, case study	yes	this paper

Table 1 summarises the main features that distinguish the proposed work from existing, related works. It enriches the discussion with a rapid overview of the main outcome of the presented paper with respect to the analysed state of the art.

Our proposed approach integrates the three dimensions of SCM (Birkel & Müller, 2021): (D1) Supplier partnership, (D2) Manufacturing flow management and (D3) Customer Service and also the key factors related to the adoption of AM that affect SCM.

Addressing RQ1, therefore, is to identify factors, with which the adoption of AM is associated and which impact on SCM; this can result in the following approach (Figure 1). According to the defined advantages of 3D printing technology in SCM namely: mechanical properties, resolution, support, speed, cost, material, build size, accuracy, the following factors, with which the adoption of AM is associated and should have impact on SCM (Birkel & Müller, 2021), (Rinaldia et al., 2021) are formulated:

D1: Supplier partnership:

- D11: Level of the alignment of production and logistics processes in the supply chain.
- D12: Storage times.
- D13: Delivery times.
- D14: Recycling costs
- D15: Supply chain resilience.

D2. Manufacturing flow management:

- D21: Supply Chain Lead Time, which represents the time required in order to transform raw material into the final product and then on to delivery,
- D22: Total Holding Costs, which reflects the costs of storing the raw material and the finished product
- D23: Total Transport Costs, which reflects the costs of moving raw material and final product
- D24: Capacity utilisation.
- D25: Assessment of human-planned processes.
- D26: Product lifecycle.
- D27: Number of repetitive, internal communications processes.
- D28: Level of safety in the working environment.

D3. Customer Service:

- D31: Customer satisfaction, which includes the sum of the total level of stock, at the end-user's and the annual, total final demand.
- D32: Time to market and respond to customer demand.
- D33: Level of individual planning,
- D34: Level of ordering autonomously.
- D35: Number of repetitive communications processes.

According to our approach it is expected, that the adoption of AM will have a positive impact on SCM, namely: shorter time to market and respond to customer demand, reduction of the incorrect assessment of human-planned processes, improved supply-chain resilience, reduction of repetitive communications processes, reduced storage time, faster delivery, lower recycling costs, longer product lifecycles, lower maintenance and transport costs with the same level of service, higher customer satisfaction and lower capacity utilisation.

The second research question (RQ2) has been investigated and conceptualised in the form of procedure, the implementation of which will allow the effects of the implementation of AM, on the process of SCM, to be monitored in manufacturing. Thanks to the measurement results obtained, it will be possible to determine the appropriate actions to improve SCM (Figure 2).

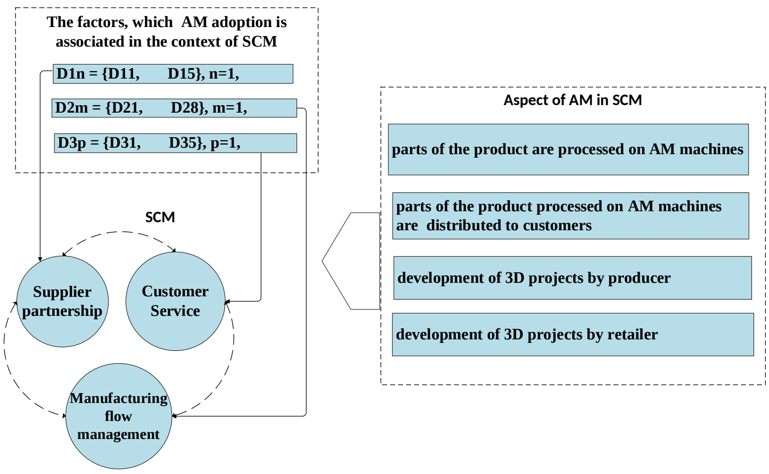

Fig. 1. Factors related to the adoption of AM that affect SCM

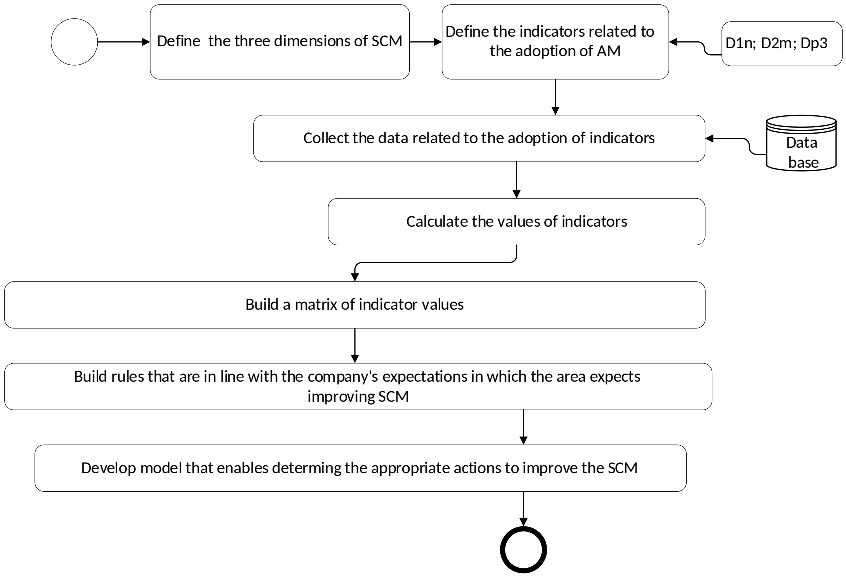

Fig. 2. Procedure to determine the appropriate actions to improve SCM

The AM process is customizable and enables the improvement of the level of sustainability, not only in manufacturing companies but also throughout the supply chain. The goal of sustainable manufacturing (SM) is to gain a competitive advantage, thanks to the balance between environmental, social and economic dimensions within a company (Jasiulewicz-Kaczmarek et al., 2021). To illustrate the managerial implications of our research results, the proposed approach (Figure 1) was applied to a real manufacturing company, in order to assist the Management Board to make projections about actions regarding improvements to SCM.

A case study

COWAN GmbH is located in Guben, Germany and is a manufacturing company that, for 20 years, has been producing everything to be found in the living space of motorhomes, such as: upholstered car seats, covered mattresses, carpets and curtains.

The company's complex supply chain consists of suppliers of basic raw materials, such as steel and/or aluminum frames, upholstery foam for headrests, produced by casting methods for specific articles in the form of rectangular solids; these are then removed and glued in the factory. The basic raw materials are also the fabrics in the beams, from which elements are factory cut with the help of a CNC machine tool; these are then sewn together by sewing machine. An important link in the supply chain are also the manufacturers of plastic products, i.e. car seat parts and plugs, which are necessary in the assembly operations carried out in the factory. Such an extensive network of suppliers from Germany, Poland, the Czech Republic and China is associated with the need to have large warehouse space in order to house the necessary inventory. The products are manufactured according to the customer's order, so the storage of finished products is limited to a minimum. Some of the manufactured goods are picked up by the customers with their own means of transport while some are delivered by the factory.

According to our approach (Figure 1) the following data was collected from a manufacturing enterprise in order to build a matrix of factors related to the adoption of AM that affect SCM values (Table 2).

An analysis of the literature sources and weaknesses in COWAN's manufacturing process shows that introducing AM would reduce the complexity of the factory's supply chain management. The changes would be justified, in particular, if the upholstery foams were not purchased for their AM. This would result in the increased ability to manufacture products in one, complete unit and the elimination of the assembly of multiple components. Knowing that the exact amount of raw material needed to produce a product on a given date would allow the stockpiling of parts to be reduced and would mean fewer work steps, a reduction in internal production costs and a shorter production process flow. In addition, the model of producing most of the components, *on-site*, reduces the logistics associated with expensive transport. AM would also en-

Table 2
Factors related to the adoption of AM that affect SCM

Dimensions of SCM	Factors relating to the adoption of AM that affect SCM	Trend within last three years (increase/decrease)	Need to improve SCM?
(D1) Supplier partnership	D11, D15	increase	YES
	D12, D13	decrease	YES
(D2) Manufacturing flow management	D24, D28	increase	YES
	D21, D22, D23	decrease	YES
(D3) Customer service	D31, D33, D34	increase	YES
	D32	decrease	YES

able the factory to manufacture customised products with design flexibility while relatively easily meeting environmental requirements.

For the production of foam components in the enterprise analyed, it would be justified to introduce two alternative methods of additive technologies. The first proposed solution is related to the fact that the metal moulds, traditionally used for the production of polyurethane foam parts are expensive, time consuming and require the use of anti-adhesive agents during the de-moulding operation. We are talking about the use of forms produced by the FDM (Fused Deposition Modelling) (Pszczółkowski et al., 2021). In this method, the applied raw material is pressed through a nozzle, heated to its melting point. The use of such a solution in industry has already been simulated in the literature (Romero et al., 2018). Another suggestion is to use Foam Additive Manufacturing (FAM), an additive manufacturing process in which components are made by applying layers of polyurethane foam with a high-pressure machine. This technology is relatively inexpensive and enables the production of large parts in a short time (Paquet et al., 2020).

Conclusions

3D printers can be installed at the manufacturer's as well as at the retailer's supply chain; this allows customer demand to be satisfied more easily. When the supply chain management combines the advantages of additive and conventional production systems and when consolidated parts options are available, all sustainability indicators improve. In the analysed case of a two-stage supply chain, in which parts are processed on AM machines and then distributed to customers, it is possible to model the problem, so as to properly use production capacity and carry out a large number of tasks in a short time. It is also important, that SCM models with AM can be used to respond quickly and flexibly to customer requirements.

Importantly, while using AM supply chains, manufacturers should focus on improving the cost of the pre-production stage. AM, in global supply chains and in addition to reducing distribution costs and implementation times, also has a positive impact on reducing greenhouse gas emissions.

The proposed framework allows Management Boards to monitor the effects of the process of SCM when implementing AM in manufacturing. Further research is required to define the corrective actions, resulting from the implementation of AM technologies in the field of SCM within a company.

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