The Impact of Additive Manufacturing on Supply Chain Resilience

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Abstract. Additive Manufacturing is changing the structure and dynamics of supply chains, influencing their ability to cope with disturbances, i.e. supply chain resilience. To date, no empirical research has investigated how using this technology influences resilience in a supply chain. Hence, the focus of this research is to investigate this knowledge gap in an industry context using survey method. The results of this research will help managers and decision-makers to determine which resilience practices to capitalize on, when using Additive Manufacturing technology, in order to better provide services and products in their supply chains.

Keywords: Additive Manufacturing · Supply chain · Resilience · Impact

1 Introduction

Additive Manufacturing (AM), also known as 3D-printing, rapid-prototyping, rapid-manufacturing, or rapid-tooling is a digital manufacturing technology that digitizes supply chains (SCs) [1]. There has been significant progress in the adoption of AM technologies over the recent years, and today it enables the possibility to revolutionize production, operations and SCs [2]. Using data from 3D computer models, AM technology can directly create objects by the incremental addition of material layers without the penalties inherent in conventional manufacturing, e.g. tooling, and thereby offering considerable opportunities for manufacturing practices. AM has the potential to cause significant changes in SCs [3, 4]. However, there is a considerable lack of empirical evidence on what are the implications of AM adoption for SCs, and most of the academic research is conceptual and limited to predictions.

Some of the expected AM impacts on SCs are related to the customer-centricity in the manufacturing process in addition to changes in the SC structure and SC capabilities, e.g., agility, flexibility, resilience [5]. AM allows for fast product and process reconfiguration in both volume and design to address the ever-changing consumer demands [6]. Moreover, decentralized production networks enabled by AM make SCs more flexible as production facilities will be located closer to the customers. One important implication of AM for SCs that has not received attention in the extant literature is supply chain resilience (SCR). A concise definition of SCR is the ability of an SC to cope with unexpected disruptions [7]. SCs are often vulnerable to numerous

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disruptions, and their effects are quite detrimental if compounded and not dealt with promptly [8]. The frequent occurrence of such disruptive events has created a notable interest in SCR [8], as endeavors to deal with them via traditional risk management techniques are inadequate [9].

The SCR construct has been analyzed and presented in the form of different frameworks throughout the extant literature. One comprehensive framework, which is also used in this research, is proposed by [10] that conceptualizes SCR as a multidimensional and hierarchical construct. The theoretical foundation for this research is based on the dynamic capability view (DCV). The DCV focuses on the competitiveness of a firm in dynamic and unpredictable markets [11]. The underlying constituents of the DCV relate to identifying strategic organizational processes, reconfiguring resources, and identifying the path to gain a competitive advantage [11]. In this light, SC management is a major strategic organizational process [12] for which SCR should be assessed; making it possible to take corrective actions by identifying and reconfiguring resources. In this research, the DCV is a relevant theoretical foundation due to the fact that AM adoption affects the strategic organizational processes [13], which consequently calls for the reconfiguration of a firm's resources to achieve competitive advantage. In view of the foregoing, the main research question is:

What are the impacts of AM adoption on the primary dimensions of SCR in an industrial context?

The rest of this paper is structured as follows: in Sect. 2, the contribution of AM technology adoption and SCR in terms of life improvement are discussed. In Sect. 3, the extant literature is reviewed, and research hypotheses are developed. In Sect. 4, the methodology that will be used in this research is described. Section 5 presents the conclusions and further work.

2 Contribution to Life Improvement

One important challenge in SCs is to efficiently deliver the right products and services to customers [3]. Being able to produce innovative, customized products via a responsive and efficient SC can bring about increased customer satisfaction [6]. At the same time, with globalization, there is a need for increasing SC efficiency. Hence, it can be stated that the implementation of SCR practices can be considered as an important strategy for businesses to increase their efficiency and to create competitive advantage [14]. Also, SCR allows companies to sustain their normal operations even when disruptive events happen [7].

In the meanwhile, the emergence of AM technology avails the opportunity of manufacturing products on demand. AM reduces the number of stages in the traditional SC, and it offers the opportunity to redesign products with fewer components (component consolidation), which leads to SC complexity reduction [15], and manufacture products closer to the final consumer (i.e. distributed manufacturing). These instances translate into less need for packaging, transportation, and warehousing [16] that lead to fewer environmental impacts and more SC efficiency. AM also enables changes in business model innovation [17] such as production by consumers, i.e. "prosumer". AM is also capable of causing fundamental changes to different aspects of SCs, e.g. SCR, as the inherent qualities of SCR such as flexibility, responsiveness, integration, and efficiency [8, 18] are influenced by this technology. Due to its additive nature, AM technology also supports sustainable production. Evaluating AM technology adoption through a life cycle perspective, sustainability improvements across the “product and process redesign”, “material input processing”, “make-to-order component and product manufacturing” and “closing the loop” stages have been identified [19].

3 Literature Review and Hypothesis Development

Using a critical literature review, we have mainly focused on the papers addressing the implications of AM technology for SCR. We used different combinations of the keywords: “Additive Manufacturing”, “3D printing”, “supply chain”, and “resilience” to search Scopus and Web of Science. The search was focused on the title, abstract and keywords field. Our search results showed that to date, no empirical research addressed the theme of the current study.

In this research, a comprehensive SCR framework proposed by [10] is used. They conceptualized SCR by using three main dimensions: proactive capability, SC design, and reactive capability. The following sections establish the connection between AM adoption and the afore-mentioned dimensions.

3.1 Additive Manufacturing and Proactive Capability

Proactive capabilities are necessary for SCs to be resilient against disruptions [9, 20, 21]. Based on the similarities in the extant literature, flexibility, integration, efficiency, redundancy, financial strength, market strength, and disaster readiness of SCs are considered as proactive capabilities of SCR [8–10, 18, 20, 22].

[1] proposes that volume and product manufacturing flexibility increase by using AM. In contrast to conventional manufacturing technologies, once AM machines are in place and running, the manufacturing of new products does not require expensive and complicated setups. This enables setting up AM machines at almost all points across the SC, including manufacturing plants at various tiers and warehouses [23].

AM adoption has a significant positive influence on SC integration [24]. This was implied through the pre-requisites of integration that firms had established within their SCs, e.g., integrated inventory management systems, integrated logistics support systems, inter-functional data sharing, etc.

[25] suggest that AM can enhance the efficiency of a SC as a result of availing postponement and waste elimination that will decrease the overall inventory level and material movement. It is also proposed that AM enables the production of light-weight products. This can result in potential considerable fuel consumption and energy savings during transport and the use phase [23].

AM enables the customization of service parts in a very short time period and eliminates significant amounts of redundancy that are accumulated in SCs to allow for parts and products to be dispatched quickly [26]. Utilizing AM can result in fewer production steps and reduce redundancy investments in production equipment [1].

The financial strength of the firms is another sub-dimension that is influenced by AM. AM drastically reduces the benefits of economies of scale attributed to conventional manufacturing. Consequently, local manufacturing firms can become more profitable [27]. Also, it is predicted that AM will have a global economic impact of approximately 550 billion US dollars per year by 2025 [27].

Regarding market strength, AM lowers barriers to market entry and provides the possibility of serving multiple markets at once. By taking advantage of the fewest possible number of assembly steps, AM fabricates products with functionally enhanced designs that can be dispatched with short lead time and makes it possible to increase the overall market strength and market responsiveness [23].

AM improvers readiness of an SC by manufacturing parts for hard to reach locations, e.g., disaster areas, and also improving the equipment uptime [28]. Based on these observations, we hypothesize that:

H1. AM adoption has a positive impact on the proactive capability of SCR.

3.2 Additive Manufacturing and Reactive Capability

The reactive aspect of SCR can be attributed to the response and recovery capabilities of firms [18, 22]. Response in SCs concerns the mitigation of disruptions in the shortest time with the least possible impacts [8]. Being able to promptly respond to market needs during critical situations is an important SCR determinant [18, 29]. AM is capable of improving SC responsiveness by manufacturing products faster. This can be due to faster time-to-market or faster production of complex products enabled by AM [1].

On the other hand, timely recovery from disruptions is also an important and distinct capability of resilient firms within their SCs [18]. In this context, for instance, if a natural disaster occurs, a deployable AM system can be installed on-site to permit addressing emergency needs with notable decreased turn-around times [28]. Based on these observations, we hypothesize that:

H2. AM adoption has a positive impact on the reactive capability of SCR.

3.3 Additive Manufacturing and Supply Chain Design

Several studies indicate the relevance between SC design and SCR. For instance, [30] identify SCR as an SC's ability to proactively design its network to predict impending disruptions and to plan effective responses accordingly. SC design can be conceptualized in terms of complexity, node density, and node criticality.

Complexity is assessed based on the number of nodes (i.e. SC members or actors) and their interconnections in an SC. Increased complexity normally causes more vulnerabilities in SC and reduces SCR [31]. AM technology enables the consolidation of many components into a single product, which reduces the number of parts in the manufacturing flow and stock-keeping units in a production system. It also allows the replacement of many assembly steps and consequently decreases complexity [15] by reducing the number of nodes and the interconnections between them in an SC.

In an SC, node density is higher when in a limited geographical area many nodes exist, which decreases SCR [31, 32]. This problem can be tackled by the decentralization of manufacturing enabled by AM technology, which can bring about significant benefits such as on-location production and prompt responses to demand [15].

Node criticality can be assessed by the importance of a node in an SC [31]. A crucial node (e.g., an important supplier whom other SC members depend on) makes the SC more vulnerable. AM can alleviate node criticality by decreasing the dependency on suppliers of complex components [1]. Based on these observations, we hypothesize that:

H3. AM adoption has a positive impact on the SC design.

4 Research Methodology

A conceptual model (Fig. 1) is proposed to measure the impact of AM adoption on the primary dimensions of SCR. In the conceptual model, the relationship between SCR and its representative sub-constructs is operationalized as reflective. This is because these sub-constructs are interconnected and interdependent [33]. For instance, to increase flexibility, integration and redundancy are essential and should be increased [18].

A questionnaire was prepared by adopting items from [10] and [24], which is based on a 5-point Likert scale. The questionnaire was then sent to an academic who specializes in the field of SCR and AM technology for revision and correction. Table 1 provides an example of the survey items. Later, the questionnaire will be sent to an expert engaged in producing spare parts using AM in a Portuguese company for review and comments. In the next step, the modified questionnaire is meant to be sent to experts in the field as a pilot survey for testing. After validation, in order to collect the necessary data, the questionnaire will be sent to experts engaged in using AM in companies across Europe.

Table 1. An example of the survey items

Construct/subconstruct	Item description
AM adoption	*Please rate the extent to which AM technology is used in your firm (1-very low; 5-very high)*
	AM in direct part manufacturing
	AM in maintenance and repair
	Please rate to what extent you believe AM technology adoption has impacted the following qualities/conditions within your firm or its supply chain: (1-very low; 5-very high)
Proactive capability	Producing different types of products to meet customer requirements
Reactive capability	Recovery in a short time
Supply chain design	Being critically dependent on a specific supplier

In order to estimate the research model, this study will apply PLS-based SEM [34] for analyzing the collected data due to the following reasons. The conceptual model developed in this research is hierarchical. PLS-based SEM is able to easily find solutions to such complex hierarchical models due to its component-based approach [34, 35]. PLS also generates less complexity when assessing hierarchical models and can present parsimonious theoretical results [36].

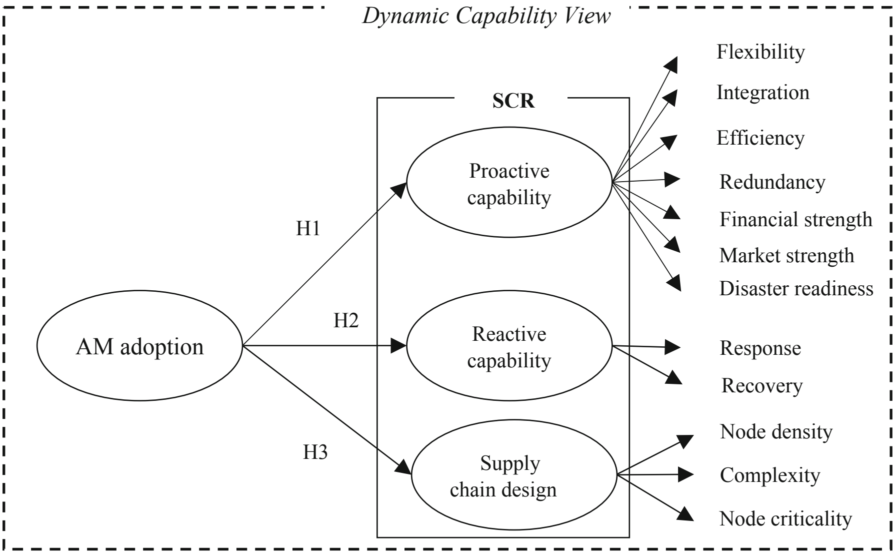

Fig. 1. Research model

5 Conclusions and Further Work

The adoption of AM technology by various industries is changing the structure and dynamics of SCs. Throughout the past few years, some attention has been given to studying such changes in the SC research. However, the studies addressing AM implications for SCs are mostly conceptual and lack empirical evidence. This gap is even more pronounced when considering the concept of resiliency in SCs. To date, no empirical research has explored the possible impacts of AM technology adoption on SCR. The results of an empirical research can help determine whether AM adoption can help to enhance SCR and consequently improve SC service levels for greater customer satisfaction and life improvement.

In this study, with the help of a comprehensive SCR framework, we managed to propose a research model that examines the impact of AM adoption on the main three dimensions of SCR, namely, proactive capability, reactive capability, and SC design. The next step would be to take the necessary actions and implement this research model in an industry setting using a deductive research approach.

Future work can extend the research model by including further variables. One suggested variable is SC performance. In this fashion, researchers can examine the direct and indirect impacts of AM adoption on SC performance via SCR.

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