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The effect of Additive Manufacturing adoption on supply chain flexibility and performance: an empirical analysis from the automotive industry

Mia Delic and Daniel Eyers

Abstract

The purpose of this paper is to provide a conceptual framework for analyzing the relationships among Additive Manufacturing adoption, flexibility, and performance in the supply chain context. No empirical study was found in the supply chain literature that specifically examines the relationships among Additive Manufacturing adoption, flexibility and performance; the paper therefore fills an important gap in the supply chain literature. The research is based on a quantitative approach using a questionnaire survey from a total of 124 medium- and large-sized European Union automotive manufacturing companies. The hypothesized relationships are tested using partial least square structural equation modeling (PLS-SEM). The research provides insights into how supply chain flexibility mediates the effect of Additive Manufacturing adoption on supply chain performance in the context of European automotive industry. Research findings indicate that Additive Manufacturing adoption positively impacts supply chain flexibility and that, in turn, supply chain flexibility positively impacts supply chain performance. This suggests that companies should focus on flexibilities in the supply chain to improve its performance. Overall, these findings provide important insights into the value of Additive Manufacturing adoption for supply chain flexibility and performance.

Keywords: Additive Manufacturing Adoption, Supply Chain Flexibility, Supply Chain Performance, Automotive Industry

1. Introduction

Supply Chain Flexibility (SCF) represents the logical progression of manufacturing flexibility, extending the idea of penalty-free change (Upton, 1995) beyond the boundaries of an individual firm to the whole supply chain (Duclos et al., 2003). Supply chain flexibility has arisen as a result of an increased focus on the contribution that supply chains make to the overall competitiveness of organizations, and is recognized by Sawhney (2006) as addressing the restrictions inherent in manufacturing that consider flexibility in terms of the individual firm, rather than the interdependencies between supply chain partners. Achieving flexibility within the supply chain allows companies to maintain both competitiveness (Blome et al., 2014; Stevenson and Spring, 2009) and efficiency (Fantazy et al., 2009) in dynamic environments (Gunasekaran et al., 2004) without compromising performance (Seebacher and Winkler, 2015). For industries characterized by shortening product lifecycles, substantial technological change, and an increased demand from customers for variety and customization, flexibility is an essential characteristic of the supply chain.

The automotive industry represents one such demanding industry that has long progressed from Henry Ford's approach based on economics of scale, standardization, and manufacturer-led innovation. Today the typical mass-produced car will have minor design refreshes on an annual or semi-annual basis, and new model introductions every few years. Simple electronics have given way to ubiquitous systems throughout the car governing comfort, control, and safety, all of which require careful integration in the manufactured vehicle. Likewise fundamental changes in propulsion technology, from fossil-fuel to electric (and hybrids in-between) further add complexity to the product offering. All these challenges are exacerbated by the need to accommodate variety and customization to satisfy individual customer preferences:

for example, the BMW 7 series has an estimated 10^{17} potential variants (Hu et al., 2008); individual tailoring could make this infinite.

Various studies have shown that innovation underpins success for automotive manufacturers both in terms of the products offered (Trautrims et al., 2017) as well as the fundamental approach taken to fulfill demand (Zhang and Chen, 2006). Without innovation to support flexibility within the supply chain, manufacturers face the perfect storm of needing to accommodate product change within their operations and supply chain, but without compromising on their overall performance in a very competitive industry. As suggested by Laosirihongthong and Dangayach (2005), competitive advantage in the automotive industry is no longer derived from low cost production, but arises from high degrees of flexibility enabled by new manufacturing technology implementation.

Many studies (e.g. Blome et al., 2014; Holweg, 2005; Manders et al., 2017) have called for a better understanding of how SCF can be achieved in practice, and within this paper we focus on how Additive Manufacturing technologies may affect the achievement of supply chain flexibility and performance in an automotive context, one of the leading industries in Additive Manufacturing adoption (Wohlers, 2019). Additive Manufacturing has been identified as enabling major change within the supply chain (Holmstrom and Partanen, 2014) by accelerating product development times (Gibson et al., 2015), enabling on-demand production with short lead times (Petrovic et al., 2011), affording new distribution channels (Eyers and Potter, 2015), changing market structures (Weller et al., 2015), and supporting a wide variety of supply chain structures (Ryan et al., 2017). However, despite these examples of potential improvement for the supply chain, as yet explicit consideration of SCF for Additive Manufacturing is extremely limited. Numerous studies have suggested that Additive Manufacturing can simplify the supply chain (e.g. Chan et al., 2018), with the extreme case being the only ‘supplier’ is the raw material provider (Mellor et al., 2014); however, this is disintermediation, not flexibility. Indeed, whilst such simplification may be attractive, Eyers (2015) found that a combination of few material suppliers (due to industry consolidation) combined with restrictions over asset specificity fundamentally hindered the achievement of flexibility within the Additive Manufacturing supply chain.

Conceptually, the adoption of Additive Manufacturing has much to offer in the achievement of flexibility in the supply chain. Already there is evidence to suggest that Additive Manufacturing technologies can play an important role in the achievement of manufacturing flexibility within the factory (e.g. Eyers et al., 2018), and these capabilities may play an important role within the supply chain. For example, Additive Manufacturing technologies are well established in supporting New Product Development activities, allowing firms to conduct in-house prototyping of new products.

However, automotive development is frequently a collaborative activity that brings together a multitude of players within the supply chain, and Additive Manufacturing already easily facilities the electronic sharing of design files together with the localised production of prototypes for each partner. In such scenarios automotive companies can readily incorporate new partners in the supply chain (i.e. sourcing flexibility), allowing them to collaborate and produce physical prototypes easily – something that cannot be achieved in many conventional technologies. Looking to the future, and building on the ideas of Khajavi et al. (2014) around spare part inventories, manufacturers could use the on-demand capabilities of Additive Manufacturing to produce spares as-demanded by customers, rather than holding expensive warehouses of stock that has uncertain demand. Moreover, by exploiting the potential postponement flexibility to pause production until the product is actually needed, Additive Manufacturing could help automotive firms manage the challenge of deploying design changes in-lifecycle. By not committing to expensive inventories of spare parts, automotive companies could update their designs to reflect feedback from the market, correcting known problems without the need to scrap inventories.

Although research on Additive Manufacturing has increased significantly over recent years (Ryan et al., 2017), it is still lacking in operations management and supply chain management literature (Schniederjans, 2017; Weller et al., 2015). Existing research has typically emphasized technological aspects of Additive Manufacturing, but in recent years a growing body of literature has focused on the commercialization of the technologies for industrial applications in various sectors (e.g. Niaki and Nonino, 2017; Thomas-Seale et al., 2018), most of which have employed qualitative case-based research (e.g. Mellor et al., 2014). Whilst Additive Manufacturing literature suggests the technologies may offer improvements to the supply chain (e.g. Cotteleer and Joyce, 2014; Giffi et al., 2014), to-date, there is still no quantitative empirical evidence how Additive Manufacturing adoption differentiates supply chains from its competitors in terms of flexibility and performance improvements. Addressing this research gap, the aim of the current study is **to examine the relationship between Additive Manufacturing adoption and supply chain flexibility, and the consequential impact on supply chain performance in an automotive context.**

The reminder of the paper is organized as follows. Section 2 provides the literature review and theoretical background for Additive Manufacturing adoption, and supply chain flexibility and performance dimensions. Then Section 3 presents the research framework, including hypothesis development. Section 4 explains the research methodology and uses data to test the hypotheses, followed by a discussion and managerial implications in Section 5. Finally, the paper concludes with Section 6, discussing the research limitations and future developments.

2. Literature review and theoretical background

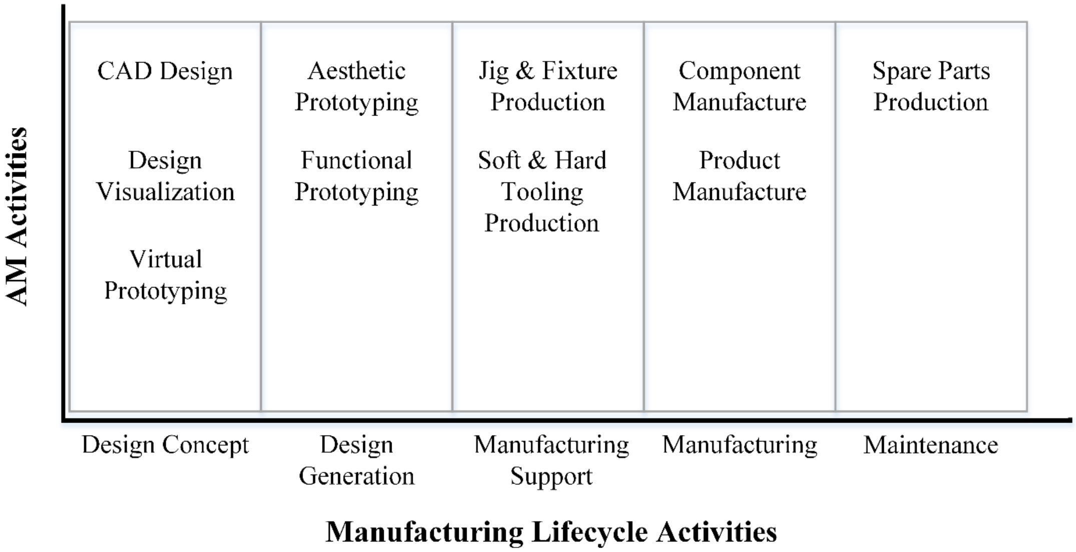
2.1. Additive Manufacturing adoption

Additive Manufacturing refers to a set of process technologies that can directly produce parts through the incremental addition of material layers of joining materials, using data from 3D computer models (BSI, 2015). There are a wide range of Additive Manufacturing processes and corresponding material options (see, e.g., Gibson et al., 2015; Ngo et. al, 2018; Wohlers, 2019). Sometimes called ‘3D printing’ or ‘rapid manufacturing’, Additive Manufacturing can be considered a general-purpose manufacturing technology by virtue of its ability for ‘frictionless’ manufacturing that negates product-specific jigs, fixtures, dies, or cutting tools (Hedenstierna et al., 2019). As a promising innovation technology, Additive Manufacturing offers significant opportunities for existing production processes (e.g. Chan et al., 2018; Ng et al., 2015; Schniederjans, 2017; Weller et al., 2015). As technologies mature and new materials become available, Additive Manufacturing has seen an exponential growth in a variety of manufacturing industries (Gardan, 2015), including automotive, aerospace, medical, and electronics (Ghobadian et al., 2018). However, various limitations still hinder adoption (e.g. Schoinochoritis et al., 2015; Thomas-Seale et al., 2018; Weller et al., 2015).

As leaders in modern production development, automotive manufacturers are also one of the first Additive Manufacturing adopters and, together with industrial machines and aerospace industry, spearhead the implementation of Additive Manufacturing technologies in the production processes (Wohlers, 2019). Although the ‘standard’ production strategy for the automotive industry is mass production (Zhang and Chen, 2006), volatile customer demands force original equipment manufacturers (OEMs) to search for flexible production technologies in order to remain competitive. Digital engineering adoption, including Additive Manufacturing, is shown to be extremely useful in raising the flexibility of some aspects of operations (Eyers et al., 2018), which is also expected for the automotive industry especially in the product development stage. Adoption of Additive Manufacturing in the automotive industry has evolved from prototype production activities, which is still leading activity in Additive Manufacturing usage among commercial vehicle manufacturers, to the production of final parts for vehicle concept models (SmarTech Market Publishing, 2015). Several automotive manufacturers are advanced commercial Additive Manufacturing adopters, such as BMW Group in printing components for in-series production (BMW Group, 2018) and VW Audi in tooling (Vialva, 2019); however, final component production for use on-vehicle is still almost exclusively related to motorsports producers (i.e. Toyota Motorsport GMBH). As Additive Manufacturing becomes standard practice in vehicle development and production, Ghobadian et al. (2018) expect automotive manufacturers will mostly use Additive Manufacturing in producing engine parts and other critical components.

When considering the adoption of Additive Manufacturing by industry, it is useful to consider how the progress of its evolution supports adoption within different stages of the manufacturing lifecycle (Figure 1). Initially the technologies were employed in design prototyping and modelmaking, and then subsequently developed for tooling and functional product manufacture (Wohlers, 2019). Currently 28.4% of Additive Manufacturing output achieves functional end-use components; the remainder mainly being in prototyping, tooling and mouldmaking, fixtures, and research (Wohlers, 2019). This emphasis has led authors such as Ghobadian et al. (2018) to suggest the technologies are in a formative phase characterized by high levels of uncertainty and expectation. This premise for general adoption of Additive Manufacturing is in-line with the adoption development model in the automotive industry context (Giffi et al., 2014), suggesting that most of the automotive industrial manufacturers still use Additive Manufacturing to produce specific prototypes, with only few advanced commercial manufacturers using Additive Manufacturing for printing final components.

Figure 1 Opportunities to utilise Additive Manufacturing technologies throughout the product lifecycle



Furthermore, whilst there is the opportunity to use Additive Manufacturing for spare part production, only a few commercial examples exist, and there are many technical challenges to overcome (Ryan and Eyers, 2017). Hence whilst many studies have suggested Additive Manufacturing will revolutionize manufacturing, perhaps a more realistic perspective is for Additive Manufacturing to be a complimentary technology to supplement conventional approaches (Chan et al., 2018). In this scenario, Additive Manufacturing remains a contributor to all stages of the automotive lifecycle, but without being the sole dominating approach.

2.2. Supply chain flexibility

Supply chain flexibility (SCF) has evolved from well-established origins in manufacturing flexibility research (e.g. Olhager and West, 2002; Upton, 1995), and extends the idea of change without trade-offs from the individual firm to the whole supply chain to remain competitive in increasingly complex business environment (Stevenson and Spring, 2007; Vickery et al., 1999). As with manufacturing flexibility, existing literature has suggested many supply chain flexibility definitions (e.g. Beamon, 1999; Sanchez and Perez, 2005), but effectively they all agree SCF represents a tool with which respond to changes in the volatile environment, without excessive performance loses (Manders et al., 2017; Zhang et al., 2002). The SCF concept has been subject to a range of methodological approaches, and a summary is shown in Table 1 which emphasizes that explorations of SCF can employ a multitude of methods, showing exemplar studies for each.

Table 1 Methods employed in principal SCF research papers

Research method employed	Publication(s)
Case study	Pujawan, 2004; Stevenson and Spring, 2009; Gosling et al., 2010; Soon and Udin, 2011; Yi et al., 2011; Purvis et al., 2014; Thome et al., 2014; Fayezi et al., 2015
Conceptual	Duclos et al., 2003; Lummus et al., 2003; Kumar et al., 2006; Tiwari et al., 2015; Manders et al., 2017, Yu et al., 2018
Delphi study	Lummus et al., 2005; Chuu, 2014
Model building	Nagarajan et al., 2013; Sokri, 2014; Seebacher and Winkler, 2015
Simulation	Garavelli, 2003; Chung et al., 2010; Kemmoe et al., 2013; Fischer et al., 2014
Survey	Vickery et al., 1999; Sanchez and Perez, 2005; Swafford et al., 2006; Fantazy et al., 2009; Merschmann and Thonemann, 2011; Moon et al., 2012; Blome et al., 2014; Gligor, 2014; He et al., 2014; Jin et al., 2014; Um, 2017; Rojo et al., 2018

Since flexibility depends on numerous interdependent factors (Seebacher and Winkler, 2015), it is very difficult to measure SCF using single metric. Several different approaches and conceptualizations of SCF have been proposed in the existing literature (e.g. Fantazy et al., 2009; Gosling et al., 2010; Rojo et al., 2018; Sanchez and Perez, 2005; Stevenson and Spring, 2009; Vickery et al., 1999), and whilst the approaches and measures taken in the papers differs considerably, a useful literature synthesis by Gosling et al. (2010) highlights that principally SCF has been considered in terms of vendor flexibility (i.e. flexibility provided by individual firms) and sourcing flexibility (i.e. the ability to gain flexibility in the supply chain by selection and deselection of suppliers).

Previous work on manufacturing flexibility has usefully delimited flexibility from the internal and external perspective (Upton, 1995), where internal flexibility concerns what the manufacturing system can do, and external perspectives concern what the customer perceives the system to be capable of. Extending this notion, Zhang et al. (2003) define flexibility competencies (the internal abilities of the manufacturing system) and flexibility capabilities (the types of flexibility that manifest as a result of the flexibility competencies). It is useful to apply this logic to SCF, where definitions of vendor flexibility effectively concern the flexibility capabilities of individual vendors that are achieved through their flexibility competencies. Sourcing flexibility is then how easily a supply chain can be reconfigured to exploit vendor capabilities (Gosling et al., 2010), and so is more about co-ordination of resources, rather than the inherent flexibility of those resources.

From the Additive Manufacturing perspective, there has been little attention paid to the SCF concept (Eyers, 2015), and given the inconsistencies in general definitions there is the need to develop an appropriate conceptualization for SCF that can be operationalized for Additive Manufacturing. Usefully, Eyers et al. (2018) have already made the linkage between flexibility competencies and capabilities in their work, and building on these ideas a new conceptualization of SCF for automotive Additive Manufacturing is explained in Section 4.1., within the construct development.

2.3. Supply chain performance

Supply chain performance (SCP) represents a construct which measures and quantifies the efficiency and effectiveness of the supply chain processes (Beamon, 1999; Li et al., 2006; Maestrini et al., 2018) in strengthening the market position. In order to evolve to an efficient and effective supply chain, supply chain management needs to be assessed for its performance (Gunasekaran et al., 2004). According to Balocco et al. (2011), efficiency seeks to maximize the output with the minimum input by reducing costs and waste (i.e. cost-related performance), while effectiveness aims to achieve supply chain optimization by increasing customer satisfaction (i.e. service-related performances). Often companies overemphasize efficiency improvements, and by neglecting effectiveness fail to achieve innovation goals (Zokaei and Hines, 2007). In order to enhance effectiveness, companies need to strive for innovation maximization in all possible areas, and Additive Manufacturing adoption is one of the viable investments for promoting rapid innovation and product design modifications (Chan et al., 2018), resulting with the increased customer satisfaction. Furthermore, as effectiveness seeks to be as flexible and customer oriented as possible, this again justifies the investment in Additive Manufacturing adoption as it contributes to flexibility advancements (Eyers et al., 2018).

Supply chain management seeks improved performance through the effective use of resources and capabilities (Maestrini et al., 2018), and non-financial metrics are crucial in measuring and fostering the improvement of performance of contemporary supply chains (e.g. Field and Meile, 2008; Gimenez et al., 2012). As Perona and Miragliotta (2004) suggested, selected performance measures should always include both effectiveness and efficiency data.

Because of its importance in measuring success of the supply chain management, SCP measurement has received significant attention from the researchers and practitioners in recent years (Katiyar et al., 2018).

Table 2 Dimensions on SCP adopted from the existing literature

Performance dimension	Description	Notable Author(s)
Supplier-oriented performance	Producer's perceptions of the key suppliers' performance in the context of quality, flexibility, delivery etc.	Baofeng, 2012; Beamon, 1999; Li et al., 2006; Liao et al., 2010
Customer-oriented performance	The performance of producers in servicing customers in the context of quality, flexibility, delivery in the downstream supply chain	Baofeng, 2012; Beamon, 1999; Lee et al., 2007
Cost-containment performance	Cost and output activities, inventory holding costs and sales growth	Lee et al., 2007; Liao et al., 2010
Time-based performance	The time required to new product development, the time required to produce the product and delivery speed	Lee et al., 2007; Liao et al., 2010
Reliability performance	The order fulfillment rates, inventory turnover rate, safety stocks, obsolete inventories and the number of product guarantee claims	Banomyong and Supatn, 2011; Beamon, 1999; Lee et al., 2007; Liao et al., 2010

Given the complexity of SCP issues, there are many conceptual frameworks and discussions on SCP measurements in the literature. For instance, Lee et al. (2007) and Liao et al. (2010) have largely covered different dimensions of performance (i.e. reliability, cost-containment, customer-oriented, supplier-oriented), while Baofeng (2012), for example, focused only on operational performance constructs (i.e. supplier and customer-oriented performance). To develop a SCP construct, this research used the framework presented by Gunasekaran et al. (2004), who emphasized the importance of using effectiveness and efficiency measures, along with the number of prior studies measuring performance in the supply chain processes (Table 2) identified in the literature review. In line with the above literature, and expert opinion from UK Russell Group University in the process of variable and construct development, this study adopted previously validated items with a high level of reliability and validity to measure SCP.

3. Research framework and hypothesis development

Building on the literature review of Section 2, this section develops the research framework and hypotheses used in this study.

3.1. Linking Additive Manufacturing adoption with supply chain flexibility

Eyers et al. (2018) build on the concept of flexibility competences and capabilities in their Additive Manufacturing work, which was itself posed by Zhang et al. (2003) for manufacturing more generally. This research focuses specifically on the SCF competencies enabled by Additive Manufacturing adoption, which in turn provide SCF capabilities. A detailed literature review identified three SCF constructs (i.e. production flexibility, postponement flexibility and sourcing flexibility) evolved from SCF competencies, which are enabled by capabilities of Additive Manufacturing.

3.1.1 Additive Manufacturing adoption and production flexibility

Achieving SCF is a key capability when dealing with technological change in the production processes and supply chain disruption (Manders et al., 2017), and one means of improving flexibility is the acceleration of product design and production, allowing companies and supply chains quick variations in production and production mixes. As the final customer requirements for custom products grow, automotive manufacturers must expand the range of products offered (Alford et al., 2000).

One of the initiatives enabling manufacturers to satisfy market demands by achieving flexibility is the adoption of Additive Manufacturing (Weller et al., 2015), which enables time and cost-effective adaptation of production processes (Giffi et al., 2014; Karevan et al., 2013; Melchels et al., 2012; Ng et al., 2015; Reeves et al., 2011; Tuck et al., 2008), fast product and process configuration in the supply chain (Chan et al., 2018; Giffi et al., 2014; Petrovic et al., 2011), also in situations of new product development (Candi and Beltagui, 2018; Chan et al., 2018; Dalenogare et al., 2018) and performing difficult design geometries (Brenne et al., 2013; Craeghs et al., 2010; Dalenogare et al., 2018; Jin et al., 2013).

In the automotive industry context, BMW for example used Additive Manufacturing in direct manufacturing to make hand tools, which helped in saving 58 percent in overall costs and project time reduction by 92 percent (Giffi et al., 2014). According to Sanchez and Perez (2005), flexibility can improve automotive company competitiveness, especially in the decision-making process of applying new technologies. However, Upton (1995) points out those managers often do not have a complete overview of flexibility but focus exclusively on machine flexibility while neglecting the flexibility of the entire system. This is a concern shared of much of the existing manufacturing flexibility research for Additive Manufacturing (Eyers et al., 2018). By extension, Gupta and Somers (1996), emphasize that focusing on flexibility in technology implementation does not necessarily lead to company and supply chain competitiveness.

3.1.2 Additive Manufacturing adoption and postponement flexibility

The need for product differentiation requires the introduction of new parts, new designs, and more efficient and faster production methods. Classically, variety and customization tend to support 'to-order' production modes (Rudberg and Wikner, 2004), where a combination of responsive production technologies and postponed operations are leveraged to satisfy demand. The ability to produce a wide range of items directly from raw materials (e.g. resins or powders) means that Additive Manufacturing can support very high degrees of postponement in production or product assembly activities (Additive News, 2018; Heralić et al., 2012; Nyman and Sarlin, 2013; Peres and Noyes, 2006), enabling companies to potentially become proactive in predicting production difficulties. Malhotra et al. (2001) have demonstrated in their research that the functionality and sophistication of CAD technology used in Additive Manufacturing positively influences time flexibility, while Chan et al. (2018) emphasize the potential for production flexibility advancements due to simplification of the production processes. Given these advances, for products that are suitable for Additive Manufacturing, in principle it is possible to postpone product differentiation until receiving the customer order, combining the standardized modules in the final assembly.

By using Additive Manufacturing, BMW Group brand Mini offers customers the ability to select custom inlays and dashboard strips online before Additive Manufacturing production and installation in the personalized vehicle (Additive News, 2018). However, in the automotive industry only about a third of car parts are produced this way, with demand normally satisfied from large, expensive inventories (Holweg, 2003). In the context of automobile production, the emphasis is put on avoiding expensive failures resulting from poor design and production or inability to timely respond to customer needs, which should have a positive effect on the flexibility of the entire supply chain. Given the short lead times in vehicle design and development enabled by this technology (Candi and Beltagui, 2018; Howard et al., 2001; Petrovic et al., 2011), companies can produce prototypes almost immediately from computer design. Moreover, once the prototype is approved, less time is needed for product configurations (Reeves et al., 2011; Tuck et al., 2008).

3.1.3 Additive Manufacturing adoption and sourcing flexibility

Sourcing flexibility is considered as the capability of the company to adapt to market changes and its ability to increase the supplier responsiveness (Gosling et al., 2010), in such a way to increase or decrease order sizes without incurring extra costs (Kumar et al., 2008) or additional time to meet customer demand (Archer et al., 2006); suppliers are able to mix different items into a delivery load so that small requests can be satisfied easily. As Additive Manufacturing adoption in the production processes reduces the minimum level of efficiency, by meeting the individual customer requirements without the significant labor or capital investment required as in conventional manufacturing processes (Cotteleer and Joyce, 2014; Ford et al., 2014; Giffi et al., 2014), it is expected to affect the sourcing flexibility as it enables efficient production at different levels of output and order sizes. Also, the demonstrated production flexibility in Additive Manufacturing context (Chan et al., 2018) helps suppliers in coping with changing production variety and order sizes (Ford et al., 2014), one of the key dimensions in sourcing flexibility.

Likewise, the automotive industry is characterized by constant pressure to reduce the supplier base and to develop relationship with key suppliers (Ambe and Badenhorst-Weiss, 2010). Involving suppliers in early product development can improve flexibility (Sanchez and Perez, 2005; Schmenner and Tatikonda, 2005), and reduce product development time and costs (Stevenson and Spring, 2007). By adopting Additive Manufacturing, some of the first-tier suppliers in the automotive industry are involved in designing components and finished products while OEMs simultaneously help them to improve production processes. Both OEMs and suppliers use Additive Manufacturing to support decision-making at the product design stage (Delic et al., 2019; Giffi et al., 2014), and this is further facilitated with the latest innovation in Additive Manufacturing automation software - Supplier Integration Network – which helps OEMs to coordinate production and post-processing activities with their existing suppliers (AMFG, 2018). Additive Manufacturing adoption by all means contributes to development of the so-called tier 0.5 suppliers, which implies the rationalization of the supplier base and close collaboration in supporting faster changes and innovations for automobiles (Giffi et al., 2014).

In conclusion, this section has provided a detailed review on the explicit links between specific dimensions of the Additive Manufacturing and supply chain flexibility with a focus on the automotive industry. Table 3 summarizes identified SCF competencies used in SCF construct development, which are shown to be influenced by Additive Manufacturing adoption in the existing literature. While supply chain flexibility in general is well established concept, this review has shown there has been little focus on SCF capabilities enabled by Additive Manufacturing adoption. Thus, to ascertain the direct impact of Additive Manufacturing adoption on supply chain flexibility, the following hypotheses are proposed:

Hypothesis 1. Additive Manufacturing adoption is positively related to the automotive supply chain flexibility.

Hypothesis 1a. Additive Manufacturing adoption is positively related to the production flexibility in automotive supply chains.

Hypothesis 1b. Additive Manufacturing adoption is positively related to the postponement flexibility in automotive supply chains.

Hypothesis 1c. Additive Manufacturing adoption is positively related to the sourcing flexibility in automotive supply chains.

The implications of these hypotheses are shown in Figure 2 linking Additive Manufacturing adoption and supply chain flexibility.

Table 3 SCF capabilities enabled by Additive Manufacturing adoption

SCF Capability	SCF Competencies		Literature
Production flexibility	SCF_PF1	Developing many new products per year	Chan et al. (2018); Giffi et al. (2014)
	SCF_PF2	Performing multiple design activities concurrently	Brenne et al. (2013); Candi and Beltagui (2018); Dalenogare et al. (2018)
	SCF_PF3	Handling a number of new product development projects in design at a given time and reasonable cost	Chan et al. (2018); Craeghs et al. (2010)
	SCF_PF4	Managing the time and cost to perform new design activities concurrently	Candi and Beltagui (2018); Dalenogare et al. (2018); Giffi et al. (2014); Karevan et al. (2013)
	SCF_PF5	Managing the time and cost to develop new products	Chan et al. (2018); Candi and Beltagui (2018); Dalenogare et al. (2018); Giffi et al. (2014); Petrovic et al. (2011)
	SCF_PF6	Modifying features and specifications of existing products	Chan et al. (2018); Melchels et al. (2012); Ng et al. (2015); Reeves et al. (2011); Tuck et al. (2008)
	SCF_PF7	Managing a varying mix of products in the market place	Chan et al. (2018); Schniederjans (2017)
	SCF_PF8	Managing the time and cost of performing difficult and nonstandard products	Candi and Beltagui (2018); Dalenogare et al. (2018); Jin et al. (2013)
Postponement flexibility	SCF_PPF1	Ability of keeping products in their generic form as long as possible, in order to incorporate the customer´s product requirements	Candi and Beltagui (2018); Howard et al. (2001); Nyman and Sarlin (2013); Petrovic et al. (2011)
	SCF_PPF2	Postponing product design and configurations until the customer orders are specified	Additive News (2018); Heralić et al. (2012)
	SCF_PPF3	Postponing production of product until the customer orders have actually been received	Additive News (2018); Peres and Noyes (2006)
	SCF_PPF4	Postponing final product assembly activities until the last possible position in the supply chain	Nyman and Sarlin (2013); Peres and Noyes (2006)
Sourcing flexibility	SCF_SF1	Operating efficiently and profitably at different levels of output	Ford et al. (2014); Giffi et al. (2014)
	SCF_SF2	Your relationship with suppliers in managing the changing environment	AMFG (2018); Giffi et al. (2014)
	SCF_SF3	Your suppliers coping with changing production volume	Chan et al. (2018); Cotteler and Joyce (2014)
	SCF_SF4	Your suppliers coping with changing production variety	Chan et al. (2018); Cotteler and Joyce (2014)
	SCF_SF5	Range of delivery frequency and possible order sizes	Ford et al. (2014)
	SCF_SF6	Costs and time implications of changing the schedule	Chan et al. (2018)

3.2. Supply chain flexibility and supply chain performance

The second hypothesis deals with the interaction between the SCF choices of automotive manufacturers and their SCP. The complexity of modern markets coupled with strong competition requires ever faster adaptation of companies and supply chains to dynamic market changes. Competitive SCP can come from a variety of sources, but is most sustainable when it is difficult to imitate. To minimise the negative effects of product variety and customization on SCP, manufacturers strive for continuous improvements in supply chain flexibility (Um, 2017). Additive Manufacturing adoption-enabled capabilities represent one potential source of differentiation and are directly associated with the flexibilities in the supply chain; in turn these flexibilities are directly associated with the creation of competitive performances (Gosling et al., 2010), by mitigating the negative impacts of product variety on SCP (e.g. Scavarda et al., 2010). The preceding section considered how Additive Manufacturing may influence supply chain flexibility, and many of these capabilities are directly linked to SCP dimensions. For instance, Additive Manufacturing enabled production flexibility, reflected in managing time and cost in developing existing and new products (e.g. Candi and Beltagui, 2018; Chan et al., 2018; Dalenogare et al., 2018; Karevan et al., 2013) or difficult and nonstandard product designs (e.g. Chan et al., 2018; Craeghs et al., 2010; Jin et al., 2013), may directly influence cost and time-based performance capabilities (i.e. quick and inexpensive introduction of new products to the market, short manufacturing lead times, or reductions in outbound costs). Furthermore, postponement flexibility in product design and configurations until receiving customer orders, enabled by Additive Manufacturing adoption (e.g. Nyman and Sarlin, 2013; Peres and Noyes, 2006), may also influence cost, reliability and customer-oriented performance capabilities by responding quickly to changes in market demand and customer requirements, and increasing order fill rate, or by reducing inventory-holding costs and safety stocks. Finally, sourcing flexibility, enabling suppliers to operate efficiently at different levels of production volume and varieties as a product of Additive Manufacturing adoption (e.g. Chan et al., 2018; Cotteler and Joyce, 2014; Ford et al., 2014; Giffy et al., 2014), will likely affect supplier-oriented performance capabilities by enabling suppliers to quickly modify or introduce new products into the market.

A flexible supply chain enables quick placement of new and existing products on the market in the required quantities, and flexibility in the delivery process. Vickery et al. (1999) demonstrated that SCF contributes significantly to the competitiveness of supply chains. Sanchez and Perez (2005) explored the relationship between SCF dimensions and firm performance in automotive industry. However, the results relevant to the SCF cannot be limited to the performance of a particular company, but should also include other members of the supply chain. Fantazy et al. (2009) and Tipu and Fantazy (2014) conclude that different dimensions of SCF have different effects on the SCP, including financial and non-financial performance, such as time-based performance and customer satisfaction. In addition, Lummus et al. (2003) point out that SCF leads to customer satisfaction (i.e. customer-oriented performance) and minimization of inventory (i.e. cost-containment performance). Chavosh et al. (2011) demonstrated that flexibility influences the efficiency of the supply chain through reliability of deliveries, where reliability is explained as the company's ability to meet its delivery obligations and delivery speeds (i.e. reliability performance). Also, a number of other empirical researches support the link between performance and flexibility of the supply chain (e.g. Aprile et al., 2005; Fantazy et al., 2009; Gligor et al., 2015; Jin et al., 2014; Liao et al., 2010; Swink et al., 2005; Vickery et al., 1999).

Unlike the well-established manufacturing flexibility concept, SCF still represents an insufficiently explored area. Therefore, the impact of flexibility on performance in the supply chain context offers a pertinent research opportunity (Fantazy et al., 2009). We recognize that there is limited research concerning the expected SCP impact of SCF in the automotive supply chain, especially in the context of Additive Manufacturing adoption. However, in accordance with the above discussion, this research expects that SCF enables automotive companies to achieve superior performance. Thus, the second set of hypotheses is as follows:

Hypothesis 2. Supply chain flexibility is positively related to the automotive supply chain performance.

Hypothesis 2a. Supply chain flexibility is positively related to the supplier-oriented performance in automotive supply chains.

Hypothesis 2b. Supply chain flexibility is positively related to the customer-oriented performance in automotive supply chains.

Hypothesis 2c. Supply chain flexibility is positively related to the cost-containment performance in automotive supply chains.

Hypothesis 2d. Supply chain flexibility is positively related to the time-based performance in automotive supply chains.

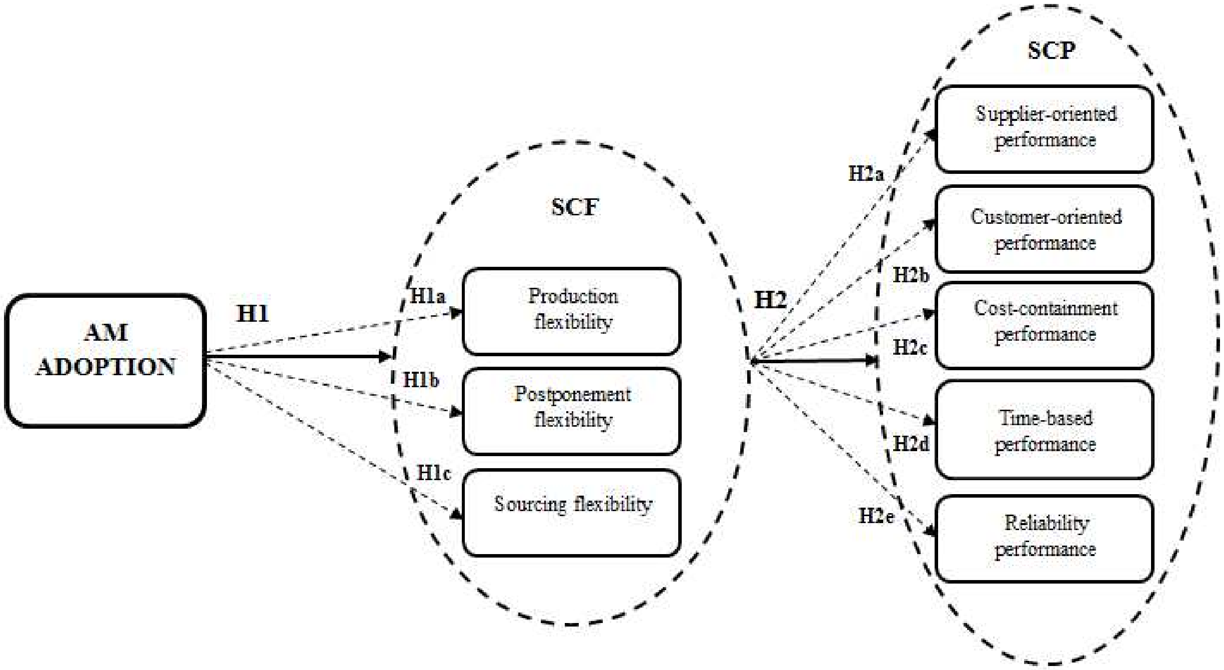
Hypothesis 2e. Supply chain flexibility is positively related to the reliability performance in automotive supply chains.

3.3. Research framework

In this section, a conceptual research framework is developed based on detail literature review and expert opinion. The proposed model for this study is provided in Figure 2; the framework clearly shows the expected links among three variables: Additive Manufacturing

(AM) adoption, supply chain flexibility (SCF) and supply chain performance (SCP). For clarity, the framework does not show all direct paths among SCF and SCP dimensions suggested in hypotheses H1a-H1c and H2a-H2e. The basic model hypothesizes that the Additive Manufacturing adoption will initiate the development of SCF dimensions. As a result, the introduction of SCF influences the SCP.

Figure 2 Research framework



4. Methodology and results

4.1. Survey design and instrumentation

The research is based on a quantitative approach using a questionnaire survey to collect data pertaining to the research hypotheses, because of the latent nature of the constructs under consideration (Hazen et al., 2017). The current study is part of a larger survey-based body of work by the authors to understand the impact of Additive Manufacturing on automotive supply chains, of which one exsisting paper (Delic et al., 2019) provides a detailed evaluation of supply chain integration on supply chain performance.

Four activities preceded the process of variable and construct development: (1) a detailed review of the literature to identify potential items for inclusion; (2) presentation of the proposed items to eighteen academic experts from operations, supply chain, and automotive research centres at a UK Russell Group University; (3) questionnaire pilot testing on 10 automotive OEMs and suppliers; (4) large sample testing via online Qualtrics survey from March to June 2016. Items were revised as needed and the final version is given in Table A1 (Appendix).

The construct measures (AM_1-AM_8) for operationalizing the concept of Additive Manufacturing adoption (Table A1) were developed based on the qualitative insights from the field of Additive Manufacturing adoption in production processes and the automotive industry (e.g. Droge et al., 2004; Eyers, 2015; Wohlers, 2019). The respondents were asked to rate the extent of application of eight technological tools (AM_1-AM_8, Table A1) supporting Additive Manufacturing adoption in production processes, from 1-very low to 5-very high. A similar approach was taken in Agostini and Nosella (2019), who measured the level of adoption of industry 4.0 technologies (including Additive Manufacturing). Also, two auxiliary question (Chou et al., 2017) items (AM_9 and AM_10), describing the level of and respondent's satisfaction with the level of Additive Manufacturing adoption, were added in the research questionnaire. The multi-item reflective measures for the SCF and SCP constructs, as shown in Table A1, were adapted from scales established in extant research (refer to Section 2.2. and 2.3): 21 items affecting postponement flexibility, production flexibility, and sourcing flexibility (Fantazy, 2007; Fantazy et al., 2009; Liao, 2008; Sanchez and Perez, 2005), one of the most frequently used SCF dimensions in previous papers (Manders et al., 2017); and 27 items affecting supplier-oriented performance, customer-oriented performance, cost-containment performance, time-based performance, and reliability performance (Banomyong and Supatn, 2011; Baofeng, 2012; Beamon, 1999; Lee et al., 2007; Li et al., 2006; Liao et al., 2010), selected SCP dimensions (Table 2). The measures for SCF and SCP constructs are based on self-reported data, as the nature of the research instrument used assumes anonymity to respondents (Jobber, and O`Reilly, 1996). However, despite the limitations of the methods employed, the use of non-financial metrics in large scale surveys is crucial in measuring improvement in the supply chains (Gimenez et al., 2012). All variables were measured through managerial perceptions by using five-point Likert scale ranging from 1=strongly disagree to 5=strongly agree. The final version of the questionnaire consisted of three main parts with a total of 58 items (Table A1), translated to English, Croatian, French, German, and Italian.

As the existing literature confirms the lack of quantitative support for Additive Manufacturing enabled supply chain advances (e.g. Waller and Fawcett, 2014), this study adopted the PLS-SEM method which is considered powerful and the most appropriate tool for the prediction and theory building exploratory research, where the relationships have not been previously tested (Hair et al., 2011; Henseler et al., 2014). Furthermore, the research model developed in this study (Figure 2) is hierarchical and complex, containing 9 constructs and 58 items; because of its component-based approach, PLS-SEM is able to easily find solutions to complex hierarchical models (Hair et al., 2013). In addition, in PLS-SEM methodology a smaller sample size can be sufficient to acquire an acceptable level of statistical power (Hair et al., 2011), as is the case in this study. Finally, PLS has been widely used in the supply chain research (e.g. Hazen et al., 2017; Yadlapalli et al., 2018).

4.2. Sampling

Medium and large companies in the production of motor vehicles sector (NACE Rev. 2, Division 29) in the 28 European Union countries were established as the object of study. The target population numbered 3,400 companies (Eurostat, 2015), covering a variety of business subjects from the automotive supply chain (assemblers, suppliers and OEMs). The initial sample of 2,546 companies was obtained from the company database Amadeus, containing information on around 21 million companies across Europe (https://amadeus.bvdep.com/), from which 1,269 available e-mail addresses were valid. As Amadeus database offers multiple contacts from each company, the survey was addressed to the company directors, manufacturing and R&D managers, and supply chain or product innovation managers, who were expected to be most familiar with the research field.

Table 4 Sample structure

Characteristic	*n (%)*	*Companies AM adopters*
Legal form		
public listed company	41 (33.06%)	29 (70.73%)
limited company	52 (41.93%)	31 (59.61%)
Partnership	13 (10.48%)	9 (69.23%)
sole proprietorship	8 (6.45%)	5 (62.50%)
Other	10 (8.06%)	4 (40.00%)
Position in the supply chain		
tier two supplier	20 (16.12%)	13 (65.00%)
tier one supplier	42 (33.87%)	21 (50.00%)
Assembler	29 (23.38%)	22 (75.86%)
OEM	33 (26.61%)	22 (66.66%)
Number of employees		
51-100	12 (9.67%)	5 (41.66%)
101-250	20 (16.12%)	11 (55.00%)
251-500	12 (9.67%)	7 (58.33%)
501-1000	25 (20.16%)	17 (68.00%)
over 1000	55 (44.35%)	38 (69.09%)
Annual turnover		
10-25 mil EUR	29 (23.38%)	17 (58.62%)
>25-50 mil EUR	13 (10.48%)	8 (61.53%)
>50-100 mil EUR	18 (14.51%)	13 (72.22%)
over 100 mil EUR	65 (52.41%)	40 (61.53%)

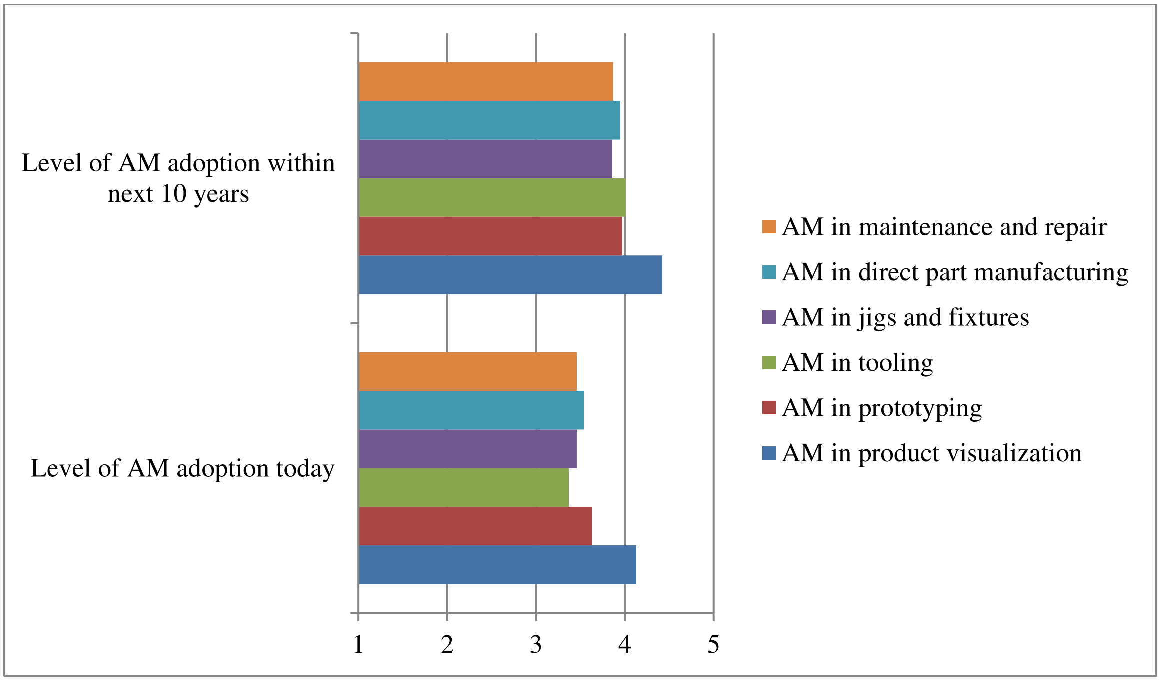
Remark: AM = Additive Manufacturing; OEM = original equipment manufacturer

A total of 124 completed responses out of 1,269 received questionnaires make the final survey sample, corresponding to a satisfactory response rate of 9.8%, which is considered adequate for partial least squares structural equation modeling (PLS-SEM) analysis as the minimum sample size is 50 respondents (Haenlein and Kaplan, 2004). Nevertheless, the response rate can be considered acceptable comparing with recent research in the field of automotive supply chain management (e.g. Droge et al., 2004; Marodin et al., 2016).

Table 4 shows the structure of business entities that participated in the study according to the legal form, position in the supply chain, the number of employees and the annual turnover. With regard to the initial sampling framework of medium and large companies (according to total number of employees and annual turnover), Table 4 shows that the final sample with around 33 percent of medium and 66 percent of large companies is adequate for data analysis. Also, the research sample covers the great part of upstream automotive supply chain, from suppliers participating at any level of the production processes (i.e. tier two and tier one suppliers) to assembly plants and OEMs. Altogether 62 suppliers were represented among the responses, compared to 29 assemblers and 33 OEMs. The presented sample profile shows the data was obtained from heterogenous group of companies, which contributes to confidence in the research findings. Considering the level of Additive Manufacturing adoption in production processes by EU member states who participated in this research, over 60 percent of companies (i.e. 78 out of 124 analyzed) in the production of motor vehicles and motorcycles have adopted Additive Manufacturing in any of the stages of production process (see details in Figure 3). The distribution of Additive Manufacturing adoption varied from 50 percent among suppliers to 75 percent among assemblers and OEMs. Also, the number of Additive Manufacturing adopters slightly increases with the number of employees and annual turnover. For instance, 69% of large companies whose number of employees exceeds 1,000 have adopted Additive Manufacturing in the production processes, while the proportion of Additive Manufacturing adopters among medium-sized companies (with less than 100 employees) is slightly above 40%. Also, considering the annual turnover, over 70% of large companies (> 50 mil EUR annual turnover) are Additive Manufacturing adopters, while the share of medium-sized Additive Manufacturing adopters (< 25 mil EUR annual turnover) is less than 60%. These results are not surprising considering that large companies are capital-intensive in order to achieve economies of scale.

In order to gain insight into the distribution of Additive Manufacturing applications across different product lifecycle stages, Figure 3 analyzes responses on each of the issues related to the Additive Manufacturing adoption in companies' production processes today and within the next 10 years. The highest level of Additive Manufacturing adoption is apparent in product visualization (4.13) and prototyping (3.63). The lowest rating is assigned to the Additive Manufacturing adoption in tooling (3.37), which was somewhat unexpected given the existing literature points out that Additive Manufacturing has revolutionized tooling and mold production. On the other hand, a relatively high rating is given to the level of Additive Manufacturing adoption in direct part manufacturing (3.54) although majority of researchers consider Additive Manufacturing as production innovations in its infancy. However, BMW recently reported it had 3-D printed its one millionth components in series production, a window guide rail using HP Fusion technology for 100 parts in 24 hours (Goehrke, 2018). Furthermore, to get insight into the perspective development of Additive Manufacturing adoption in production processes of European automotive supply chains, Figure 3 analyzes the perspectives of Additive Manufacturing adoption in production processes in the next 10 years. Again, the highest rating is given to the level of Additive Manufacturing adoption in product visualization (4.42), while the lowest rating is assigned to the Additive Manufacturing adoption in maintenance and repair (3.87). An encouraging observation is that Additive Manufacturing adoption in direct part manufacturing generated almost the same average scores (3.95) as the Additive Manufacturing adoption in prototyping (3.97), showing that respondents consider Additive Manufacturing technologies as an extremely useful upgrade to existing production processes and will probably continue to invest in Additive Manufacturing adoption in the near future.

Figure 3 Distribution of Additive Manufacturing adoptions across product lifecycle stages



Legend: 1- very low; 5-very high

Among 124 respondents, 78 were companies representing Additive Manufacturing adopters in any of the product lifecycle stages. Since the structural model analyzes the adoption of Additive Manufacturing in the supply chain context (Figure 2), further empirical analysis and hypotheses testing was carried out only on 78 manufacturing companies Additive Manufacturing adopters. Similar approach was taken in Small and Yasin (1997) research, who examined the level of advanced manufacturing technologies (AMT) adoption.

4.3. Assessment of psychometric properties

Reliability and validity of the constructs, when assessing reflective measurement models (Hair et al., 2011), were examined before analyzing the path structures of the model. As the methods for internal consistency, Cronbach alpha value and composite reliability scores were used. A Cronbach alpha value greater than 0.7 was accepted as a good indicatior of reliability, while item-total correlation measures should be above 0.5 (Hair et al., 2010). The results reported in table A1 show that all of the constructs are reliable as their corresponding Cronbach alpha values are above the 0.7 threshold. Hence, the internal consistency of the indicatiors is acceptable. Furthermore, the evaluation of composite reliability (CR) in SmartPLS 2.0 program is also used to estimate the internal consistency of a construct. The results show that the composite reliability values are greater than 0.8 for all constructs, which is above minimum threshold of 0.5 as recommended by Hair et al. (2011), thus confirming the reliability of the constructs.

Table 5 Correlation matrix

	SF	PF	PPF	AM	SOP	COP	RP	FP	CCP	TBP
SF	-									
PF	0.706	-								
PPF	0.529	0.523	-							
AM	0.480	0.662	0.521	-						
SOP	0.547	0.533	0.537	0.548	-					
COP	0.569	0.527	0.561	0.526	0.743	-				
RP	0.409	0.342	0.452	0.400	0.623	0.603	-			
FP	0.522	0.705	0.473	0.484	0.402	0.379	0.310	-		
CCP	0.186	0.208	0.311	0.164	0.280	0.387	0.489	0.240	-	
TBP	0.542	0.546	0.367	0.454	0.501	0.379	0.613	0.426	0.466	-

The Average Variance Extracted (AVE) with satisfactory level above 0.5 (Hair et al., 2010) was examined to test the convergent validity of the instrument. The results from the Table A1 indicate acceptable levels of AVE, i.e. above 0.5 for all latent constructs. Discriminant validity was established by comparing the AVE square root values with other correlation values among the latent variables (Enkel et al., 2016). The results shown in Table 5 indicate that discriminant validity of all constructs is well established.

To double-check the discriminant validity, a Heterotrait-Monotrait Ratio (HTMT) for latent constructs was analysed, as suggested by Henseler et al. (2015). HTMT coefficient value less than 1 indicates good validity. Using a PLS bootstrap procedure, the results shown in Table 6 show that the discriminant validity is well established.

Table 6 HTMT Ratio

	SF	**PF**	**PPF**	**AM**	**SOP**	**COP**	**RP**	**FP**	**CCP**	**TBP**
SF										
PF	0.821									
PPF	0.664	0.635								
AM	0.552	0.762	0.653							
SOP	0.667	0.622	0.690	0.630						
COP	0.675	0.599	0.697	0.595	0.881					
RP	0.508	0.409	0.597	0.488	0.780	0.736				
FP	0.587	0.774	0.573	0.548	0.454	0.415	0.377			
CCP	0.235	0.245	0.403	0.197	0.337	0.453	0.629	0.272		
TBP	0.664	0.645	0.471	0.525	0.609	0.446	0.781	0.481	0.568	

Finally, the results from the Table A1 show that all latent constructs satisfy the convergent reliability criterion (Hair et al., 2013), i.e. all factor loadings show values above (0.4), acceptable for exploratory studies (Dwaikat et al., 2018). These findings conclude that the latent variables in the measurement model are internally consistent and reflect the appropriate levels of convergent reliability and discriminand validity, acceptable for the model structural analysis.

4.4. Hypothesis testing

After constructs were validated, the hypothesized relationships were tested by using the partial least square structural equation modeling framework (PLS-SEM). Due to the characteristics of the model and the sample, this method is appropriate for analysis (Hair et al., 2010). The exogenous variable (i.e. AM adoption) was modeled as first-order construct. The endogenous variables (i.e. SCF and SCP) were modeled as second-order constructs with several first-order constructs.

In the first step the coefficients of determination (R^2) to evaluate the predictive power of the model of the two endogenous variables were examined, for which Chin (2010) suggests a cut-off value of 0.4 as indicating substantial path structures. For SCF and SCP R^2 scores were 0.439, and 0.536, respectively. Furthermore, to assess the impact of the individual latent exogenous variables on the endogenous ones, the effect sizes (f^2) were analyzed. Henseler et al. (2015) suggested threshold values of 0.02, 0.15, and 0.35 to classify the effect sizes into small, medium and large. The result showed that SCF has a strong influence on endogenous variable SCP ($f^2 = 0.391$). The Stone-Geisser test (Q^2), providing that all values of latent endogenous constructs are greater than 0, was conducted to assess the predictive relevance of the model (Henseler et al., 2015). The results in Table 7 show the predictive relevance of the corresponding exogenous constructs for the endogenous construct SCF (Q^2=0.168), and SCP (Q^2=0.195).

Table 7 Predictive relevance analysis (Q^2)

Variable	SSO (sum of squares observation)	SSE (sum of squares error prediction)	Q^2
SCF	1404.000	1167.880	0.168
SCP	1638.000	1318.304	0.195

Finally, the bootstrap procedure tested the path coefficient sizes and statistical significance of the relationships between the latent variables in the structural model. The standardized path coefficient (β) equal or greater than 0.1 (Eggert and Serdaroglu, 2011), and *t*-values equal or greater than 1.96 (Hair et al., 2013) indicate highly significant outer model loadings. The results obtained by the bootstrap procedure are shown in Table 8. Observing the path coefficients, *t*-values and *p*-values of the inner model, the results confirm that Additive

Manufacturing adoption has statistically significant positive impact on automotive SCF (β=0.663, t=12.161, p>0.000). Hence, H1 is supported. Furthermore, the results confirm that Additive Manufacturing adoption has statistically significant positive impact on each SCF dimension (i.e. production flexibility, postponement flexibility and sourcing flexibility) (t>1.96, p<0.000). Therefore, hypotheses H1a-H1c are supported.

Then, SCF has statistically significant positive impact on automotive SCP (β=0.391, t=3.616, p<0.000), supporting the H2. Equally, the results confirm that SCF has statistically significant positive impact on each SCP dimension (i.e. supplier-oriented performance, customer-oriented performance, cost-containment performance, time-based performance and reliability performance) (t>1.96, p<0.001). Accordingly, the second set of hypotheses H2a-H2e of this research is also accepted. Thus, the *t*-value, *p*-value results and all bootstrap confidence intervals that do not include value 0 show that all indirect relations show a significant level of influence, which means accepting all sub-hypotheses in the proposed model (Figure 2).

Table 8 Results of hypothesis testing based on partial least squares analysis

	Structural relations	Original sample (***β***)	Sample mean (M)	Standard deviation (STDEV)	*t* value	*p* value	Direct relation of the second-order latent construct to endogenous latent construct
H1	AM → SCF	0.663	0.674	0.055	12.161	0.000	-
H1a	AM → PF	0.615	-	-	12.695	0.000	0.663
H1b	AM → PPF	0.476	-	-	7.246	0.000	0.663
H1c	AM → SF	0.583	-	-	11.920	0.000	0.663
H2	SCF → SCP	0.391	0.393	0.108	3.616	0.000	-
H2a	SCF → SOP	0.326	-	-	3.511	0.000	0.391
H2b	SCF → COP	0.333	-	-	3.460	0.001	0.391
H2c	SCF → CCP	0.238	-	-	3.268	0.001	0.391
H2d	SCF → TBP	0.285	-	-	3.208	0.001	0.391
H2e	SCF → RP	0.333	-	-	3.455	0.001	0.391

5. Discussion

This study provides quantitative evidence as to the value of Additive Manufacturing adoption in the achievement of both flexibility and performance within the supply chain. The data show that all hypotheses are fully supported, and in this section we provide an overview of the results, together with a discussion on the implications for research and practice.

For H1, the direction of the influence of Additive Manufacturing adoption on SCF is consistent with the observations made in Section 3.1 for modern technology adoption. For technologies *in general* the literature suggests that such linkages are to be expected (e.g. Duclos et al., 2003; Swafford et al., 2006), but ours is the first to evidence these relationships *specifically for* Additive Manufacturing through a quantitative empirical study. Given Additive Manufacturing is typically identified as offering very different capabilities relative to conventional manufacturing processes, it cannot be assumed that the general assumptions would hold true for these innovative technologies. The results confirm a significant positive effect of Additive Manufacturing adoption on each SCF dimension, with the strongest influence for Production Flexibility. This construct embodies many of the classic flexibility types (e.g. product, mix, volume flexibilities), and emphasizes how flexibility competencies of Additive Manufacturing can be employed in the achievement of changed production requirements, whether it be for new product development, or in the provision of variety/customization of existing offerings. Given the increasing need to accommodate such changes within the automotive industries, the achievement of such flexibility offers clear benefits for manufacturers. For example, commercial examples such as Twikbot are now publically available, allowing customers to create their own customizations for Mini cars, which then connects to BMW's digital production centre for customized parts to be manufactured using Additive Manufacturing, and combined with conventionally produced parts. This capability offers much promise for the industry; though more research is needed to understand how to manage Additive Manufacturing for optimum benefits in practice. Specifically, there is a need for much more work to understand which attributes of SCF have greatest commercial advantage through Additive Manufacturing – and how then to link these to overall production strategies.

For H2 we find a positive and significant influence of SCF on SCP, supporting the viewpoint that achieving SCF is a valuable activity for firms to engage with. If this were not the case, then the achievement of SCF would be futile; flexibility is only a useful attribute if it leads to purposeful outcomes (Zhang et al., 2003). Whilst H1 evidences that SCF can be achieved through Additive Manufacturing, H2 provides the performance motivations to do so. The results demonstrate that every SCP dimension is positively influenced by the achievement of SCF, emphasizing the importance of taking a ‘whole chain’ perspective. The data highlights benefits for customers and suppliers alike, with the strongest influence being found in customer-orientated performance (emphasizing the ability to achieve responsiveness to changing demands), and reliability performance (focusing on optimization of production and supply). Traditionally the automobile industry has struggled to manage the conflicting requirements of satisfying unique customer demand without affecting the scale economy operations that normally promote reliability, and this major issue often results in suboptimal inventory management practices (e.g. Holweg, 2003), leading to costly inventories of products that do not exactly meet the customer requirement, but are essential to avoid extremely long lead times. The ability to produce customized products on-demand is widely acknowledged as a key attribute of Additive Manufacturing technologies, but yet little research has explicitly considered the technologies with respect to the operations concept of postponement. For conventional manufacturing this is part of the strategic toolkit employed to yield benefits from the supply chain (e.g. Yang and Burns, 2004), and consideration of the differences arising from Additive Manufacturing now need to be explored.

These findings suggest that Additive Manufacturing has implications beyond the often-cited benefits for prototyping and new product design for automotive manufacturers. Existing theory suggests supply chain flexibility is an effective response to demand uncertainty (Stevenson and Spring, 2007), and through such capabilities, firms can enjoy competitiveness (Sanchez and Perez, 2005). This assertion is supported by the data of this study, which suggests automotive supply chains which are flexible support the achievement of competitiveness in a wide range of important performance measures. However, whilst automotive applications are popular outlets for Additive Manufacturing production (Wohlers, 2019), they constitute a tiny proportion of the overall manufacturing output of the sector. Even with the flexibility and performance benefits identified in this study, it would be naïve to suggest Additive Manufacturing will displace the economies enjoyed in conventional manufacturing approaches anytime soon: mass produced cars will remain mass produced, and will employ mass production technologies to achieve their objectives. This does not mean that Additive Manufacturing will not have a significant impact within industry. What is more likely in the near future is the benefits recognized in this study will be useful to support and enhance supply chains that predominantly use conventional manufacturing technologies. For example, Additive Manufacturing could be used to produce spare-parts on-demand in a location near to the customer, leveraging the SCF and SCP benefits to offer low-volume, quick-response, competitive manufacturing solutions. Already there is a growing body of literature to suggest the feasibility of such a proposition for the aerospace industry (e.g. Holmstrom and Partanen, 2014;

Khajavi et al., 2014); arguably the scale of the automotive industry makes this an even more promising opportunity.

Aside from some of the more practical opportunities raised in this study, we also identified several interesting implications for research. First, we investigated the effects of Additive Manufacturing adoption on SCF as no research was found that specifically connected these two concepts. The results confirmed that Additive Manufacturing adoption is important enabler of SCF, establishing the foundation for further research into this topic. Furthermore, we provided evidence in that SCF leads to SCP, offering additional support and clarity for prior research. We also contributed by defining SCF and SCP dimensions as several different approaches and conceptualizations have been proposed in the existing literature. Overall, these findings provide valuable insights for both research and practice in terms of better understanding Additive Manufacturing in the supply chain context.

One particularly interesting aspect of our research findings links to the temporal nature of the results. Consistent with previous studies that focus on the implications of technology on flexibility (e.g. Sanchez and Perez, 2005), this research focused on how technologies affect operations in the near-term. However, it is arguable that the introduction of new technologies and the manifestation of benefits will often incur a time-lag, and so whilst this does not diminish the findings of our work, it does present an opportunity for further studies that explore flexibility to engage in longitudinal research to better understand the longer-term implications of technology adoption.

Another important acknowledgement that must be recognized is the implication of adopting a survey methodology in this work. Whilst there are many recognized benefits of such approaches (e.g. Fink, 2017; Fowler, 2013), it is important to recognize that this comes with limitations. In our work we present judgmental and perspective managerial assessments of Additive Manufacturing, which inherently suffer issues of self-reporting bias (Donaldson and Grant-Vallone, 2002), and, given the nature of the research instrument, many of the intricacies regarding *how* and *why* cannot be collected. Indeed, in-line with Jobber and O'Reilly (1996) and Ranchhod and Zhou (2001), our results were collected from anonymous participants, precluding follow-up research where particularly interesting responses were identified. This is not to diminish the contribution of the work; ours is a first large-scale survey in the area, and produces useful and relevant results. But with these results come more questions, and there is now the need for further detailed qualitative studies to focus on exploring in greater depth how best to enable flexibility throughout the supply chain.

A final particularly interesting avenue for further exploration would be to examine whether there are specific types of companies that have better opportunities for Additive Manufacturing exploitation that others. For example, are larger companies more likely to benefit than smaller ones? Or do geographic idiosyncrasies mean that firms in certain countries have an advantage? Whilst the current study has focused on aggregate company data, there are clear benefits for using a combination of quantitative survey data together with qualitative investigation. This would enable researchers to understand the characteristics of individual companies in far more detail, making a useful extension to this work.

6. Conclusion

The unique contribution of this study is the exploration and explanation of how Additive Manufacturing adoption supports supply chain flexibility, and in turn the improvement of supply chain performance in an automotive context. In the absence of existing work in this area, we build on the established theoretical constructs for SCF and SCP, developing a conceptual model grounded in the literature base and informed by expert practitioners to ensure a robust theoretical underpinning for the work. Measurement instruments for Additive Manufacturing adoption, SCF and SCP were developed, and these were tested on automotive OEMs and its suppliers before being applied within in the empirical study.

The literature on Additive Manufacturing makes a wide range of claims about the transformative impact the technologies may have on manufacturing practice. Many companies within the automotive industry have dabbled with the technologies (to varying extents, and with varying degrees of success). In the absence of quality quantaitive research, in this work we wanted to provide an empirical assessment to substantiate some of the expectations for Additive Manufacturing. Our objective for the proposed model was to analyze the contribution of Additive Manufacturing adoption in production processes to the flexibility and performance of the automotive supply chain management, through which the ability to optimize the supply chain was tested. The empirical findings have given the answer to proposed research question: Additive Manufacturing adoption has a direct positive impact on the automotive SCF; in turn, the SCF positively influences the SCP. For practitioners, this is an important observation - not only does Additive Manufacturing enable flexibility capabilities within the individual operation, but the benefits can be manifested throughout the supply chain. Hence, the results of this research reveal important insights for both academics and practitioners to successfully adopt the Additive Manufacturing technologies in the context of automotive supply chain management, and within our discussion we posit some pertinent areas for further research focusing on the strategic deployment of Additive Manufacturing in this context.

Appendix

Table A1 Measurement model results

Indicator	Item description	Factor loading	Cronbach alpha value	Average variance extracted (AVE)	Composite reliability (CR)
Additive Manufacturing adoption (AM)		**-**	**.870**	**.531**	**.899**
AM_1	CAD adoption	x	x	x	X
AM_2	CAM adoption	x	x	x	X
AM_3	AM in product visualization	0.528	-	-	-
AM_4	AM in prototyping	0.546	-	-	-
AM_5	AM in tooling	0.797	-	-	-
AM_6	AM in jigs and fixtures	0.812	-	-	-
AM_7	AM in direct part manufacturing	0.758	-	-	-
AM_8	AM in maintenance and repair	0.769	-	-	-
AM_9	Generally, we think the level of AM adoption in our company is high	0.751	-	-	-
AM_10	We are satisfied with the level of AM adoption in our company	0.806	-	-	-
Supply chain flexibility (SCF)		**-**	**-**	**-**	**-**
Production flexibility (PF)		-	.882	.549	.907
SCF_PF1	Developing many new products per year	0.773	-	-	-
SCF_PF2	Performing multiple design activities concurrently	0.770	-	-	-
SCF_PF3	Handling a number of new product development projects in design at a given time and reasonable cost	0.680	-	-	-
SCF_PF4	Managing the time and cost to perform new design activities concurrently	0.750	-	-	-
SCF_PF5	Managing the time and cost to develop new products	0.768	-	-	-
SCF_PF6	Modifying features and specifications of existing products	0.765	-	-	-
SCF_PF7	Managing a varying mix of products in the market place	0.704	-	-	-
SCF_PF8	Managing the time and cost of performing difficult and nonstandard products	0.710	-	-	-
Postponement flexibility (PPF)		-	.730	.552	.831
SCF_PPF1	Ability of keeping products in their generic form as long as possible, in order to incorporate the customer´s product requirements	0.724	-	-	-
SCF_PPF2	Postponing product design and configurations until the customer orders are specified	0.768	-	-	-
SCF_PPF3	Postponing production of product until the customer orders have actually been	0.799	-	-	-

	received				
SCF_PPF4	Postponing final product assembly activities until the last possible position in the supply chain	0.676	-	-	-
SCF_PPF5	Postponing final product labeling activities	x	x	x	X
Sourcing flexibility (SF)		-	.819	0.525	0.869
SCF_SF1	Operating efficiently and profitably at different levels of output	0.735	-	-	-
SCF_SF2	Your relationship with suppliers in managing the changing environment	0.747	-	-	-
SCF_SF3	Your suppliers coping with changing production volume	0.728	-	-	-
SCF_SF4	Your suppliers coping with changing production variety	0.745	-	-	-
SCF_SF5	Range of delivery frequency and possible order sizes	0.694	-	-	-
SCF_SF6	Costs and time implications of changing the schedule	0.695	-	-	-
SCF_SF7	Managing reasonably the cost of switching from one supplier to another	x	x	x	X
SCF_SF8	Managing the time and cost needed for outsourcing changing requirements	x	x	x	X
Supply chain performance (SCP)		-	**-**	**-**	**-**
Customer-oriented performance (COP)		-	.868	.603	.901
SCP_COP1	Our supply chain can quickly modify products to meet these customers` requirements	.703	-	-	-
SCP_COP2	Our supply chain can quickly introduce new products into the market	.794	-	-	-
SCP_COP3	Our supply chain can quickly respond to changes in market demand	.770	-	-	-
SCP_COP4	Our supply chain has an outstanding on-time delivery record to these customers	.832	-	-	-
SCP_COP5	Our supply chain provides high level of customer service to these customers	.778	-	-	-
SCP_COP6	The time between the receipt of customer's order and the delivery of the goods is short	.779	-	-	-
Supplier-oriented performance (SOP)		-	.866	.734	.892
SCP_SOP1	These suppliers can quickly modify products to meet our supply chains requirements	.849	-	-	-
SCP_SOP2	These suppliers can quickly introduce new products into the markets	.882	-	-	-
SCP_SOP3	These suppliers can quickly respond to changes in market demand	.839	-	-	-
SCP_SOP4	These suppliers have an	x	x	x	X

	outstanding on-time delivery record to our supply chain				
SCP_SOP5	These suppliers provide high quality materials and products to us	x	x	x	X
SCP_SOP6	These suppliers provide materials and products to us at reasonable cost	x	x	x	X
SCP_SOP7	The number of our suppliers has reduced over the past three years	x	x	x	X
Cost-containment performance (CCP)		-	.847	.736	.893
SCP_CCP1	Our supply chain system reduces inbound costs	x	x	x	X
SCP_CCP2	Our supply chain system reduces outbound costs	.836	-	-	-
SCP_CCP3	Our supply chain system reduces warehousing costs	.859	-	-	-
SCP_CCP4	Our supply chain system reduces inventory-holding cost	.877	-	-	-
Reliability performance (RP)		-	.760	.510	.838
SCP_RP1	Our supply chain system increases our order fill rate	.720	-	-	-
SCP_RP2	Our supply chain system increases our inventory turns	.802	-	-	-
SCP_RP3	Our supply chain system reduces our safety stocks	.726	-	-	-
SCP_RP4	Our supply chain system reduces our inventory obsolescence	.676	-	-	-
SCP_RP5	Our supply chain system reduces our product warranty claims	.637	-	-	-
Time-based performance (TBP)		-	.810	.637	.875
SCP_TBP1	Our supply chain introduces new products to the market quickly	x	x	x	X
SCP_TBP2	Our supply chain provides fast and on-time delivery	.762	-	-	-
SCP_TBP3	Our supply chain has a short manufacturing lead time	.789	-	-	-
SCP_TBP4	Our supply chain rapidly confirms customer orders	.804	-	-	-
SCP_TBP5	We are satisfied with the speediness of the supply chain process	.837	-	-	-

Remark: x – items excluded from the analysis after validation of the measurement model

Table A2 Legend

Abbreviation	Description
AM	Additive Manufacturing adoption
CCP	Cost-containment performance
COP	Customer-oriented performance
PF	Production flexibility
PPF	Postponement flexibility
RP	Reliability performance
OEM	Original equipment manufacturer
SCF	Supply-chain flexibility
SCP	Supply chain performance
SF	Sourcing flexibility
SOP	Supplier-oriented performance
TBP	Time-based performance

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