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# Additive Manufacturing: Empirical evidence for supply chain integration and performance from the automotive industry

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# Additive Manufacturing: Empirical evidence for supply chain integration and performance from the automotive industry

## 1. Introduction

There has been considerable progress in the development of Additive Manufacturing technologies over the last thirty years, and today it offers the potential to revolutionize production operations and their supply chains (Eyers and Potter, 2017). Using data from 3D computer models, Additive Manufacturing technologies can directly produce parts through the incremental addition of material layers (BSI, 2015), using light or heat to create objects without the penalties inherent with tooling, thereby offering significant opportunities for manufacturing practice. Additive Manufacturing has evolved from prototyping to production technology, and has become a standard practice in contemporary product development and manufacturing (e.g. Kondor *et al.*, 2013). It has been suggested that Additive Manufacturing may accelerate product development times (Gibson *et al.*, 2015), lessen product development costs (Baumers *et al.*, 2012), offer capabilities in both flexibility (Eyers *et al.*, 2018) and agility (Vinodh *et al.*, 2009), increase innovation performance (Candi and Beltagui, 2019), lessen the need for spare parts inventory holding (Khajavi *et al.*, 2014), and yield products that could not otherwise be produced with conventional technologies (TSB, 2012). For the supply chain, Additive Manufacturing has the potential to enable enormous changes (Candi and Beltagui, 2019; Christopher and Ryals, 2014; Holmström and Partanen, 2014; Waller and Fawcett, 2014), but as-yet there is notably little consensus in the literature over what will be achieved, and a severe lack of empirical evidence on which conclusions may be drawn.

One of the most popular applications for Additive Manufacturing is within the automotive industry (Wohlers, 2016), as it promises innovations in product development (Giffi *et al.*, 2014) and significant financial savings by simplifying the long and complex supply chains (Dwivedi *et al.*, 2017). In automotive industries, the huge variety and complexity of products often leads to Original Equipment Manufacturers (OEMs) outsourcing many activities in product design and manufacture to specialist suppliers, helping to simplify internal processes and minimize costs (Gobetto, 2014). Traditionally, outsourcing risks losing a firm's own internal capabilities (Handley, 2012), but with the application of Additive Manufacturing and co-operation with suppliers, OEMs may increase their R&D share in both value creation and production (Giffi *et al.*, 2014).

The adoption of new technologies is often heralded as promoting a 'competitive advantage' (e.g. D'Aveni, 2015). But, in order to create value and to obtain competitive advantage through this type of differentiation, innovation adoption (e.g. Additive Manufacturing) should leverage the power of collaboration by connecting suppliers and customers in complementary businesses (Skroupa, 2017). Contemporary perspectives suggest that real competitive advantage comes between supply chains, and this observation motivates the current study. However, as-yet there has been little research to show how a sustainable competitive supply chain advantage can be achieved through Additive Manufacturing. Given the range of potential opportunities the technologies may afford for automotive industries, this study is motivated to address this observed research gap.

The aim of this research is to identify how the adoption of Additive Manufacturing affects both supply chain performance and integration, and how these in turn affect overall firm performance. Whilst previous works have suggested general advantages for the supply chain arising from the adoption of Additive Manufacturing, most focus only on the general qualitative advantages, which do not provide the necessary quantification to understand the effect on these three attributes. Consistent with many other scholars in Operations and Supply Chain Management (Walker *et al.*, 2015) we adopt the resource-based view (RBV) in this work, through which we explore whether the adoption of Additive Manufacturing could serve as a transformation catalyser to the technologies as a firms strategic resource. We tackle this research by focusing specifically on the application of Additive Manufacturing in the automotive sector, through which we explore the following research question: How does Additive Manufacturing adoption affect automotive supply chain integration and performance?

## 2. Theoretical background and hypothesis development

This section unifies the concepts of supply chain performance, supply chain integration, and firm performance with Additive Manufacturing in an automotive context. Whilst there is scant literature linking these supply chain concepts to Additive Manufacturing, several examples from existing automotive research show some potential opportunities for the technologies, and we draw on these in our hypothesis development. In each subsection we therefore present the key theoretical concepts, link them to relevant literature examples, and develop the hypothesis that underpin our research model.

### *2.1. Additive Manufacturing adoption and supply chain performance*

Supply chain performance is a construct with a set of measures to determine efficiency and effectiveness of the supply chain (Beamon, 1999; Li *et al.*, 2006). Improving supply chain performance can positively affect the market position of the firm and strengthen its competitive edge in the marketplace. Supply chain performance has many facets (Seo *et al.*, 2014). For suppliers, supply chain performance concerns a producer's perception of its own suppliers in terms of quality, flexibility, delivery, and the like (Huo, 2012). In principle, Additive Manufacturing offers much support for supply chain performance as it promotes rapid innovation and product modifications (Dwivedi *et al.*, 2017), together with quick changes in design (Chan *et al.*, 2018). Through AM total delivery time can be reduced (Weller *et al.*, 2015), and additional costs of part complexity and variability are significantly lower than in traditional manufacturing (Simhambhatla and Karunakaran, 2015). For customers, supply chain performance concerns a suppliers performance in terms of product quality, flexibility, etc. (Huo, 2012). Again, the Additive Manufacturing literature highlights several attributes of the technologies which may positively contribute to supply chain performance in the automotive sector. This includes accelerated product development with reduced time-to-market (Dwivedi *et al.*, 2017; Giffi *et al.*, 2014), increased product differentiation (Chan *et al.*, 2018), and faster order fulfillment (Sasson and Johnson, 2016).

Aside from the supplier and customer-oriented performance, supply chain performance is often considered in terms of cost, reliability, and time performance measures. Compared to traditional approaches to manufacturing, Additive Manufacturing is typically more economical at lower production volumes thanks to the elimination of constraints such as tooling (Wohlers, 2016), but has also been identified as offering benefits to the automotive supply chain in the reduction of material usage (Gao *et al.*, 2015), lower warehousing and transportation costs (Sasson and Johnson, 2016), and decreased inventory holding costs (Dwivedi *et al.*, 2017) which are enabled through on-demand production. Such advantages have been exploited by Delphi (a Tier-1 automotive supplier) to reduce overall production costs through the adoption of Additive Manufacturing (Giffi *et al.*, 2014). Similarly, Additive Manufacturing has also shown opportunities to improve the reliability of order fulfillment, particularly by moving to responsive on-demand production to improve fill-rates, whilst reducing safety stocks and stock-out events (Chan *et al.*, 2018; Dwivedi *et al.*, 2017). Finally, Additive Manufacturing offers the potential to make a temporal contribution to supply chain performance. Timeliness of supply is an important characteristic of supply chain performance, though for the automotive industry product lifecycles are notoriously long (Gobetto, 2014), impairing the ability of companies to meet market demand quickly. In a competitive marketplace, customer demands necessitate quick time-to-market. Therefore, the application of innovative technologies and methods to improve responsiveness can support competitive advantage for supply chain members (Seo *et al.*, 2014). Additive Manufacturing in automotive supply chains has been identified as shortening the time-to-market (Dwivedi *et al.*, 2017), rapidly prototyping designs (SmarTech Publishing, 2015), and eliminating tooling (Giffi *et al.*, 2014). These capabilities have allowed Ford to prototype designs in four days (rather than four months) at less than 1% of the conventional cost (Giffi *et al.*, 2014), and Joe Gibbs Racing to reduce design and machining time from 33 to 3 days (Giffi *et al.*, 2014).

Achieving competitive advantage by adopting resources and capabilities is manifested in the resource-based view (RBV) (Huo, 2012; Newbert, 2007), which tries to explain why firm performances in the same industry can differ from each other. From the RBV perspective, this research defines Additive Manufacturing adoption as a ratio in which automotive supply chain companies use Additive Manufacturing common resources and production management processes. According to RBV, it is possible to achieve production cost synergy by using common production factors in more production units (Barney, 2014). The preceding text suggests Additive Manufacturing adoption represents a potential source of competitive advantage for supply chains; therefore, the RBV approach suggests that Additive Manufacturing should influence the proposed supply chain performance dimensions (i.e. cost-containment, time-based and reliability performance) in automotive supply chains. Also, with its capability of producing unique and customized products, Additive Manufacturing can improve automotive market responsiveness (Giffi *et al.*, 2014), and therefore satisfy increasing customer and supplier needs in automotive supply chains (i.e. influence customer-oriented and supplier-oriented performance), simultaneously creating profits and benefits of buying low volume production customized products at the mass production price (Dekker *et al.*, 2003). Based on these observations, the following hypotheses are suggested:

**Hypothesis 1.** Additive Manufacturing adoption influences automotive supply chain performance.
**Hypothesis 1a.** Additive Manufacturing adoption influences supplier-oriented performance in automotive supply chains.
**Hypothesis 1b.** Additive Manufacturing adoption influences customer-oriented performance in automotive supply chains.
**Hypothesis 1c.** Additive Manufacturing adoption influences cost-containment performance in automotive supply chains.
**Hypothesis 1d.** Additive Manufacturing adoption influences time-based performance in automotive supply chains.
**Hypothesis 1e.** Additive Manufacturing adoption influences reliability performance in automotive supply chains.

The implications of these hypotheses are shown in Figure 1 linking Additive Manufacturing adoption and supply chain performance.

### *2.2. Additive Manufacturing adoption and supply chain integration*

Supply chain integration represents the extent to which a company can collaborate with partners and manage its processes to achieve effective and efficient flows of products and services to the final customer (Huo, 2012). Increasing global pressures and changes to production strategies have forced many companies to adopt innovative solutions for supply chain management issues to improve both service and delivery quality (Laosirihongthong *et al.*, 2011). This requires firms to improve their internal production capabilities as well as integrating with supply chain partners (Frohlich and Westbrook, 2001). For the automotive industry, this leads to a transformation from ‘closed’ and technically-orientated production towards ‘open’ and collaborative innovation philosophies. Such approaches have led to the fundamental rethinking and radical redesign of business processes to achieve supply chain integration (Bennett and Klug, 2012), including improved supplier relationships, and increased need for trust between OEMs and Tier-1 suppliers (Brandes *et al.*, 2013).

Internal integration of the supply chain concerns how the functions and procedures of the focal firm are integrated and synchronized (Huo, 2012). The ‘digital’ nature of Additive Manufacturing technologies in terms of design and production are expected to promote integration between processes and functions within an automotive manufacturer. For example, Dwivedi *et al.* (2017) suggest Additive Manufacturing promotes the concept of digital inventory to meet demand inside factories, whilst Prajogo *et al.* (2018) identify Additive Manufacturing as improving data flow between departments. Focusing specifically on integration, Dalenogare *et al.* (2018) found that Additive Manufacturing supports vertical integration in different hierarchical levels of an organization.

Whilst internal integration focuses on the 'internal chain' it is also important to consider customer and supplier integration. Customer integration concerns their cooperation in new product development, and information sharing that producers can use in directing production and improving services at a lower cost (Lotfi *et al.*, 2015). Additive Manufacturing has been shown to support closer integration between manufacturer and customer in many industries, and existing research suggests this applies in the automotive context. For example, Toyota (2015) illustrates how the technologies help in customization and provide freedom for customers to choose unique features. By supporting co-creation between manufacturer and customer (Chekurov *et al*., 2018; Jiang *et al.*, 2017), greater responsiveness (Dwivedi *et al.*, 2017) and highly customized products (Weller *et al.*, 2015) can be achieved. However, whilst electronic exchange of files is straightforward (Eyers and Potter, 2015), to fully exploit co-design a strong relationship is needed between suppliers and customers. Somewhat similarly, supplier integration considers the integration between supplier and manufacturer in new product design, production and inventory planning, etc. (Lee *et al*., 2007). Notably this relationship is often overlooked in the literature, where Additive Manufacturing is often assumed to significantly disintermediate the supply chain. However, this does not represent current practice, and Mellor *et al.* (2014) identify that Additive Manufacturing requires increased collaboration with suppliers, which by extension suggests closer integration will be beneficial.

New technology implementation represents one of the best ways to promote new functionalities and performance improvements for existing products. In this regard, Additive Manufacturing adoption supports innovative production regardless of the product design complexity (Zhang *et al.*, 2014). However, Barney (2014) argued that in addition to simply adopting resources, companies need to be organized to exploit their full potential and achieve competitive advantage. Additive Manufacturing is readily available to the competition in automotive industry (Dwivedi *et al.*, 2017), and thus will not satisfy the RBV value and rarity criteria taken in isolation. From this perspective, Additive Manufacturing should therefore be embedded in management processes within supply chains. More specifically, automotive companies will obtain competitive advantage only when they integrate these advanced technologies with their basic capabilities. One obvious example is the application of Additive Manufacturing to support co-creation, providing a value proposition based on customization and personalization in vehicle design.

The application of specific tools and knowledge affects the strengthening of cooperation in the automotive industry, by partnering suppliers and sharing knowledge through organised supplier networks (Bennet and Klug, 2012). Additive Manufacturing adoption represents a tool for the efficient exchange of knowledge and production experience between OEMs, key suppliers, and customers (Toyota, 2015), demanding even greater coordination and managerial effort (Candi and Beltagui, 2019) which is crucial to achieve supply chain integration. Although the advantages of Additive Manufacturing adoption in strengthening organizational performance and creating a sustainable competitive advantage is proposed in literature (e.g. Dwivedi *et al.*, 2017; Giffi *et al.*, 2014), empirical studies have shown inconsistent results, and the mechanism which improves the supply chain integration within the automotive industry is not completely developed. The following hypotheses represent this view:

**Hypothesis 2.** Additive Manufacturing adoption influences the automotive supply chain integration.
**Hypothesis 2a.** Additive Manufacturing adoption influences the internal integration in automotive supply chains.
**Hypothesis 2b.** Additive Manufacturing adoption influences the customer integration in automotive supply chains.
**Hypothesis 2c.** Additive Manufacturing adoption influences the supplier integration in automotive supply chains.

### *2.3. Supply chain integration and supply chain performance*

The preceding two sections considered how Additive Manufacturing may influence supply chain performance and integration, developing detailed hypotheses for components of each concept. Several authors have suggested that improving supply chain integration has positive implications for supply chain performance, however the results of existing research are inconsistent (e.g. Flynn *et al.*, 2010; Halley and Beaulieu, 2009; Kumar *et al.*, 2017; Rosenzweig *et al.*, 2003; Swink *et al.*, 2007). RBV scholars have argued that integration offers companies resources that are valuable and hard to imitate (Barratt and Oke, 2007), enabling OEMs to become more market responsive (Bennett and Klug, 2012). Kamal and Irani (2014) find increasing overall supply chain performance is a key motivation for the supply chain integration, while Frohlich and Westbrook (2001) identified that companies in the supply chain with the highest level of customer and supplier integration achieve the highest level of performance in the context of service quality, delivery, productivity, market share, and profitability.

There is limited explicit research on integration in the automotive supply chain (e.g. Othman *et al.*, 2016), but we identify reasonable optimism in studies to suggest a positive relationship between supply chain integration and performance. Integrating Tier-1 suppliers within early-phase design activities has a positive impact on the success and project performance of vehicle manufacturers in terms of costs, quality, and time-to-market (e.g. Clark and Fujimoto, 1991; Droge *et al.*, 2004). Similarly, customer integration supports enhanced product quality (Danese and Romano, 2011) and the achievement of customer-focused production (Lotfi *et al.*, 2015). Furthermore, integration within automotive supply chains positively contributes to cost-containment performance (Scannell *et al.*, 2000), reliability (Panayides and Lun, 2009), and customer-oriented performance (Zhao *et al.*, 2013).

Given the lack of consensus in the literature over the relationship between supply chain integration and performance, but the encouraging emphasis found in automotive research, it is necessary to explore this relationship further in the current study. This research predicts a positive relationship between supply chain integration and supply chain performance in the automotive industry, which is additionally reinforced by Additive Manufacturing adoption. Based on the above it is hypothesized that:

**Hypothesis 3.** Supply chain integration influences supply chain performance in automotive industry.

**Hypothesis 3a.** Supply chain integration influences supplier-oriented performance in automotive supply chains.

**Hypothesis 3b.** Supply chain integration influences customer-oriented performance in automotive supply chains.

**Hypothesis 3c.** Supply chain integration influences cost-containment performance in automotive supply chains.

**Hypothesis 3d.** Supply chain integration influences time-based performance in automotive supply chains.

**Hypothesis 3e.** Supply chain integration influences reliability performance in automotive supply chains.

### *2.4. Supply chain performance and firm performance*

Firm performance considers whether the company is achieving its market-oriented and financial goals (Yamin *et al.*, 1999). Examining the impact of supply chain performance on firm performance determines the ability to positively affect the company's competitiveness. Effectiveness and efficiency are causally related as suggested by Hakansson and Prenkert (2004) who have shown that effectiveness is a direct consequence of efficient supply chain management.

An RBV perspective suggests companies can establish a competitive advantage by developing distinctive capabilities, which is reflected in its effectiveness and business results (Barney, 2014). When a company develops characteristic supply chain capabilities through supply chain integration, it is likely to improve operational competencies (Halley and Beaulieu, 2009), and achieve competitive advantage in the market (Kumar *et al.*, 2017). Customer-oriented performance can directly reduce costs, increase sales, and improve market share. For example, new product development and response to market demands will help companies to satisfy customers' demands, ultimately leading to greater market share. High service quality and customer satisfaction also generate higher income and profitability (see e.g. Huo, 2012; Vickery *et al.*, 2003). On the other hand, delivery reliability, flexibility, and customer service can lower costs and improve customer loyalty (Huo, 2012). Similarly, supplier-oriented performance also affects firm performance improvement. For example, new product development helps suppliers achieve requirements, which potentially affects product quality and market share. The importance of time-based performance in achieving competitiveness and affecting firm performance is especially highlighted in previous research (e.g. Ketchen and Hult, 2007).

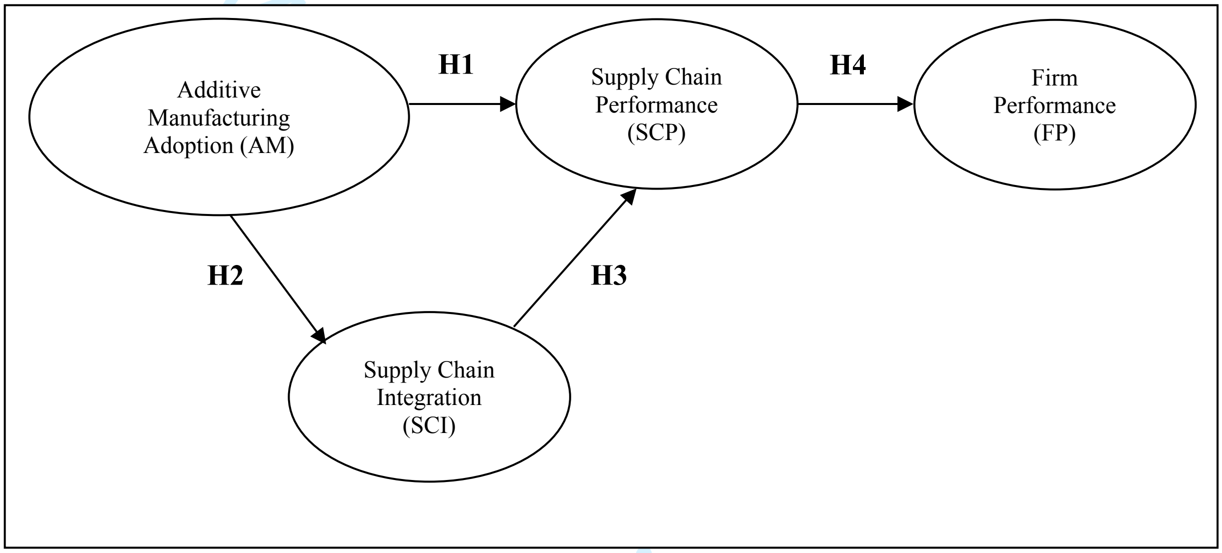
Previous research on firm performance has used financial and market criteria (e.g. Huo *et al.*, 2014), and we draw upon these in the current study. It is expected that the Additive Manufacturing adoption in production processes, through its impact on supply chain performance, will positively affect firm performance. The above arguments lead to:

**Hypothesis 4.** Supply chain performance influences firm performance in automotive industry.

### *2.5. Developing a research model for Additive Manufacturing*

The literature review found that supply chain performance, supply chain integration, and firm performance have received scant research attention in an Additive Manufacturing context. However, through the literature review the pertinent characteristics of each of these have been explored, from which Figure 1 provides an illustration of the proposed research model for this study.

**Figure 1 Research model**



## 3. Methodology

### *3.1. Research variables and measurements*

This study employed a highly structured questionnaire composed of closed-type questions with multiple choice answers. The process of variable generation and construct development was achieved through four activities (Figure 2). The final version of the research instrument was administered online (Table 7, Appendix 1), translated to English, Croatian, French, German, and Italian. Each of the items for the construct were measured using a five-point Likert item ranging from 1=strongly disagree to 5=strongly agree.

The Additive Manufacturing adoption variable represents the independent variable in the conceptual model of this paper (Figure 1). A comprehensive review of the available literature showed that the measurement instrument for the specified variable, which could be used in quantitative research, has not been developed to-date. Based on the presented qualitative insights and case studies from the field of Additive Manufacturing (e.g. Droge *et al.*, 2004; Eyers and Potter, 2017), the measurement instrument for operationalizing the concept of Additive Manufacturing adoption was developed. As computer-aided design (CAD) and computer-aided manufacturing (CAM) adoption are general components of an industrial Additive Manufacturing system (Eyers and Potter, 2017) and prerequisite for adoption, those items (AM_1-AM_2) did not prove to be valid in Additive Manufacturing adoption measurement, and therefore were excluded from the analysis after the validation of measurement model. Six key dimensions (AM_3-AM_8) define the level of Additive Manufacturing adoption within different production processes (Table 7). They derived from Wohler's research (2016) according to which Additive Manufacturing is used in direct parts production (28.1%), fit and assembly (17.5%), prototype tooling (11.3%), metal castings (10.8%), visual aids (10.40%) and prototypes (9.50%). Since the literature suggests to use auxiliary questions in developing the research variables to prove the authenticity of the answers (e.g. Chou *et al.*, 2017), two more items describing the respondents satisfaction with the level of Additive Manufacturing adoption (AM_9 and AM_10) were added in the research questionnaire (Table 7).

**Figure 2 Variables and construct development process**

| **Phase** | 1. Design | 2. Testing | | 3. Application |
|---|---|---|---|---|
| **Activity** | Questionnaire Item Selection | Questionnaire Refinement | Questionnaire Testing | Large Sample Testing |
| **Method** | Literature Review | Expert Presentation | Piloting | Online Qualtrics Survey |
| **Technique** | Narrative Review | Workshop with 18 Academics | Pilot to ten automotive companies | 1269 Companies Surveyed March-May 2016 |
| **Outcome** | 71 Items for Investigation | Questionnaire Refined | Questionnaire Validated | 124 Completed Responses for analysis |

The supply chain integration variable is operationalized in three dimensions: (1) internal integration (Huo, 2012; Narasimhan and Kim, 2001; 2002), (2) supplier integration (Frohlich and Westbrook, 2001; Huo, 2012; Narasimhan and Kim, 2002), and (3) customer integration (Frohlich and Westbrook, 2001; Huo, 2012; Narasimhan and Kim, 2002).

Given the complexity of supply chain performance concept issues, this research adopts a balanced approach using a conceptualization of performance as a higher order construct, and operationalizes the variable in five dimensions (Table 7): (1) supplier-oriented performance (Beamon, 1999; Frohlich and Westbrook, 2001; Huo, 2012; Li *et al.*, 2006), (2) customer-oriented performance (Beamon, 1999; Frohlich and Westbrook, 2001; Huo, 2012), (3) cost-containment performance (Lee *et al.*, 2007), (4) time-based performance (Lee *et al.*, 2007), and (5) reliability performance (Banomyong and Supatn, 2011; Beamon, 1999; Gunasekaran *et al.*, 2001; Liao *et al.*, 2010; Ralston *et al.*, 2015).

Firm performance, as a multidimensional concept, can take into account different performance measures (e.g. Frohlich and Westbrook, 2001; Huo, 2012; Narasimhan and Kim, 2002; Rosenzweig *et al.*, 2003; Wisner, 2003; Yamin *et al.*, 1999) and in this study includes market share, growth in market share, sales growth, profit growth, return on investment (ROI), ROI growth, net profit margin/rate on sales (ROS), and ROS growth (Table 7).

### *3.2. Sampling and data collection*

The research was conducted on medium and large companies (min. 50 employees and 10 mil EUR annual turnover) in the production of motor vehicles sector (NACE Rev. 2, Division 29) in the 28 European Union countries. According to Eurostat (2015), the target population numbered 3,400 companies, covering business subjects from various levels of automotive supply chain (assemblers, Tier-1, sub-tier suppliers and OEMs). The sampling frame was taken from Amadeus database and a mailing list of 2,546 companies was downloaded, from which 1,269 companies were valid.

A total of 146 questionnaire responses were collected, of which 22 were incomplete and subsequently removed from the sample, which allows adequate comparability of questionnaires to all measured parameters (Kline, 2011). Therefore, the total of 124 completed responses out of 1,269 received questionnaires make the final survey sample, with a satisfactory response rate of 9.8%. This is adequate for partial least squares structural equation modeling (PLS-SEM) analysis used in hypotheses testing, where the minimum sample size is 50 respondents (Haenlein and Kaplan, 2004). Comparing the obtained response rate with existing research in the field of automotive supply chain management, several previous studies have successfully used considerably less respondents (e.g. Droge *et al.*, 2004; Marodin *et al.*, 2016).

The analysis of the collected data was conducted in three phases: (1) descriptive analysis, (2) analysis of the applied measurement model, and (3) analysis of the structural model using the 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. Additive Manufacturing adoption) was modeled as first-order reflective construct. The endogenous variables (i.e. supply chain integration and supply chain performance) were modeled as second-order constructs with several reflectively identified first-order constructs. The firm performance endogenous variable was modeled as first-order reflective construct. A two-step analytical approach was taken. Reliability and validity of the measurement model were examined before analyzing the path structures of the model. SmartPLS 2.0 software was used for model estimations, while the normality of the data was calculated in the PASW-IBM SPSS software.

## 4. Results

### *4.1. Descriptive analysis*

Table 1 shows the structure of business entities who participated in the study according to the legal form, position in the supply chain, the number of employees, and the annual turnover. The research spans the entire automotive supply chain, from material suppliers to assembly plants and OEMs.

**Table 1 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*** | | |
| sub-tier | 3 (2.41%) | 3 (100.00%) |
| tier-2 supplier | 17 (13.70%) | 10 (58.82%) |
| tier-1 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%) |

Table 2 shows the Additive Manufacturing adoption in production processes by EU member states who participated in the research. Considering the main countries producing motor vehicles and motorcycles (Czech Republic, France, Italy, Germany, UK), over 60% of companies have adopted Additive Manufacturing in their production processes. The empirical analysis for the remainder of this study is conducted on the 78 manufacturing companies who have adopted Additive Manufacturing in their production processes.

**Table 2 The use of Additive Manufacturing in production processes by country**

| **Country** | **The use of AM in production processes** | | |
|---|:---:|:---:|:---:|
| | Yes | No | Total |
| Austria | 1 | - | 1 |
| Belgium | 1 | 2 | 3 |
| Czech Republic | 5 | 7 | 12 |
| Finland | - | 1 | 1 |
| France | 16 | 1 | 17 |
| Croatia | 10 | - | 10 |
| Italy | 10 | 8 | 18 |
| Hungary | 1 | 1 | 2 |
| Netherlands | 2 | - | 2 |
| Germany | 16 | 10 | 26 |
| Portugal | 2 | 2 | 4 |
| Romania | - | 1 | 1 |
| Slovakia | 1 | 1 | 2 |
| Slovenia | - | 3 | 3 |
| Spain | 1 | - | 1 |
| Sweden | - | 1 | 1 |
| UK | 14 | 6 | 20 |
| **TOTAL** | **78 (62.90%)** | **46 (37.09%)** | **124** |

### 4.2. *Analysis of the measurement model*

Before data analysis, variables are put on a strict evaluation of reliability and validity. As the method for indicator reliability, Cronbach alpha value was used where the reliability coefficient around 0.7 value was accepted (Kline, 2011). Table 7 shows the reference levels of the Cronbach alpha coefficients, where all measurement items have a satisfactory level of reliability over 0.7 (Enkel *et al.*, 2016).

To test the convergent validity of the instrument the following criteria were used (Table 7): (1) factor loadings with satisfactory level above 0.7 (Duarte and Raposo, 2010), (2) composite reliability (CR) with satisfactory level above 0.5 (Wilden *et al.*, 2013), and (3) Average Variance Extracted (AVE) with satisfactory level above 0.5 (Hair *et al.*, 2010). The results from the Table 7 (Appendix 1) show that all latent constructs satisfy the convergent validity criterion, i.e. all variable factor loadings show values above (0.7). Then, CR is higher than 0.8 for all constructs which is above minimum threshold of 0.5 as recommended by Wilden *et al.* (2013). Likewise, convergent validity was tested through AVE whose values are also satisfactory, i.e. above 0.5 for all latent constructs (Hair *et al.*, 2010). Therefore, one can conclude that the variables in the measurement model are internally consistent and reflect the appropriate convergent reliability and the constructs validity.

**Table 3 Discriminant validity**

| | SI | CI | AMT | SOP | COP | RP | FP | CCP | TBP | II |
|---|---|---|---|---|---|---|---|---|---|---|
| SI | - | | | | | | | | | |
| CI | 0.616 | - | | | | | | | | |
| AM | 0.357 | 0.523 | - | | | | | | | |
| SOP | 0.505 | 0.488 | 0.548 | - | | | | | | |
| COP | 0.537 | 0.524 | 0.526 | 0.743 | - | | | | | |
| RP | 0.385 | 0.464 | 0.400 | 0.623 | 0.603 | - | | | | |
| FP | 0.294 | 0.368 | 0.484 | 0.402 | 0.379 | 0.310 | - | | | |
| CCP | 0.381 | 0.274 | 0.164 | 0.280 | 0.387 | 0.489 | 0.240 | - | | |
| TBP | 0.293 | 0.535 | 0.454 | 0.501 | 0.379 | 0.613 | 0.426 | 0.466 | - | |
| II | 0.691 | 0.644 | 0.392 | 0.429 | 0.488 | 0.254 | 0.339 | 0.358 | 0.265 | - |

Legend: AM = Additive Manufacturing adoption; CCP = cost-containment performance; CI = customer integration; COP = customer-oriented performance; FP = firm performance; II = internal integration; RP = reliability performance; SCI = supply chain integration; SCP = supply chain performance; SI = supplier integration; SOP = supplier-oriented performance; TBP = time-based performance

The next step determined whether the AVE of each construct surpassed the highest square correlation with other constructs (Enkel *et al.*, 2016). All constructs were found to show an acceptable level of discriminant validity (Table 3). In the final step, a Heterotrait-Monotrait Ratio for latent constructs was analysed, as suggested by Henseler *et al.* (2015), where the discriminant validity between two constructs is proved if the coefficient values do not exceed 0.9, as shown in Table 4.

**Table 4 Heterotrait-Monotrait Ratio**

| | SI | CI | AMT | SOP | COP | RP | FP | CCP | TBP | II |
|---|---|---|---|---|---|---|---|---|---|---|
| SI | | | | | | | | | | |
| CI | 0.748 | | | | | | | | | |
| AM | 0.414 | 0.635 | | | | | | | | |
| SOP | 0.593 | 0.602 | 0.630 | | | | | | | |
| COP | 0.628 | 0.626 | 0.595 | 0.881 | | | | | | |
| RP | 0.473 | 0.600 | 0.488 | 0.780 | 0.736 | | | | | |
| FP | 0.327 | 0.416 | 0.548 | 0.454 | 0.415 | 0.377 | | | | |
| CCP | 0.450 | 0.335 | 0.197 | 0.337 | 0.453 | 0.629 | 0.272 | | | |
| TBP | 0.350 | 0.675 | 0.525 | 0.609 | 0.446 | 0.781 | 0.481 | 0.568 | | |
| II | 0.796 | 0.771 | 0.460 | 0.504 | 0.561 | 0.309 | 0.368 | 0.424 | 0.316 | |

Legend: AM = Additive Manufacturing adoption; CCP = cost-containment performance; CI = customer integration; COP = customer-oriented performance; FP = firm performance; II = internal integration; RP = reliability performance; SCI = supply chain integration; SCP = supply chain performance; SI = supplier integration; SOP = supplier-oriented performance; TBP = time-based performance

Considering the exploratory character of the study aiming to develop a new model, based on the obtained CR results, factor loadings, AVE, Cronbach alpha and discriminant analysis tests, one can conclude that latent constructs are reliable, internally consistent, convergent, with a satisfactory level of discriminant validity, and as such acceptable for the model structural analysis.

### *4.3. Analysis of the structural model*

Since the validity and reliability of the model was confirmed in the previous section, the next step is the structural model analysis, testing the proposed hypotheses using the PLS-SEM framework. Two algorithms, PLS and bootstrap algorithm, and two sets of guidelines for the evaluation of the models were used for the coefficient and relation analysis.

To evaluate the predictive power of the model the coefficients of determination ($R^2$) for the three endogenous variables were examined. The $R^2$ score for supply chain performance was found as 0.536; for firm performance it was 0.208, and for supply chain integration we observed a value of 0.244. Lew and Sinkovics (2013) suggest a cut-off value of 0.1 as indicating substantial path structures acceptable.

Then, the effect sizes ($f^2$) to assess the impact of the individual latent exogenous variables on the endogenous variables were analyzed. Threshold values of 0.02, 0.15, and 0.35 were used to classify the effect sizes into small, medium and large, as suggested by Henseler *et al.* (2015). This analysis showed that supply chain integration has a strong influence on supply chain performance ($f^2$ = 0.300). Furthermore, Additive Manufacturing adoption has a moderate impact on supply chain performance ($f^2$ = 0.159).

**Table 5 Predictive relevance analysis ($Q^2$)**

| Variable | SSO (sum of squares observation) | SSE (sum of squares error prediction) | $Q^2$ |
|---|---|---|---|
| SCI | 1404.000 | 1284.597 | 0.085 |
| SCP | 1638.000 | 1318.304 | 0.195 |
| FP | 624.000 | 548.090 | 0.265 |

Legend: FP = firm performance; SCI = supply chain integration; SCP = supply chain performance

After the effect sizes, to assess the predictive relevance of the model the Stone-Geisser test ($Q^2$) was conducted. If all values of latent endogenous constructs are greater than zero, the model has predictive significance and the observed variables are well constructed (Henseler *et al.*, 2015). We applied the blindfolding and cross-validated redundancy methods (Hair *et al.*, 2011) to identify the initial $Q^2$ value. The results in Table 5 show the predictive relevance of the corresponding exogenous constructs for the endogenous construct supply chain performance of 0.195, while the $Q^2$ value for the second endogenous construct firm performance and the associated exogenous construct is 0.265. Finally, the $Q^2$ value for the endogenous construct supply chain integration and the associated exogenous construct shows a low predictive relevance of 0.085, but considerably above 0 indicating the predictive relevance of the model for the endogenous variables.

Finally, the significance of the estimated path coefficients in the model was tested. We employed the bootstrap procedure (Table 6) to achieve insights into the significance level. The results revealed that Additive Manufacturing adoption has positive, but not statistically considerable influence on automotive supply chain performance ($\beta$=0.159, $p$>0.05). Hence, H1 is partially supported. When considering the influence of Additive Manufacturing adoption on each supply chain performance dimension (i.e. supplier-oriented performance, customer-oriented performance, cost-containment performance, time-based performance, and reliability performance), one can conclude that Additive Manufacturing adoption has positive and statistically considerable influence on each supply chain performance dimension ($p$<0.001). Therefore, hypotheses H1a-H1e are supported.

Then, Additive Manufacturing adoption has positive and statistically considerable influence on automotive supply chain integration ($\beta$=0.473, $p$<0.001), meaning that H2 is supported. When considering the influence of Additive Manufacturing adoption on each supply chain integration dimension (i.e. supplier integration, customer integration, and internal integration), one can conclude that Additive Manufacturing adoption has positive and statistically considerable influence on each supply chain integration dimension ($p$<0.001). Therefore, hypotheses H2a-H2c are supported.

**Table 6 Bootstrap standard errors and significance levels of path coefficient estimates**

| | Structural relations | Original sample (O) | Sample mean (M) | Standard deviation | *t* value | *p* value | *Direct relation of the second-order latent construct to endogenous construct* |
|---|---|---|---|---|---|---|---|
| **H1** | AM → SCP | 0.159 | 0.167 | 0.100 | 1.580 | 0.115 | - |
| **H1a** | AM → SOP | 0.466 | - | - | 6.952 | 0.000 | 0.159 |
| **H1b** | AM → COP | 0.476 | - | - | 7.086 | 0.000 | 0.159 |
| **H1c** | AM → CCP | 0.341 | - | - | 5.221 | 0.000 | 0.159 |
| **H1d** | AM → TBP | 0.408 | - | - | 5.325 | 0.000 | 0.159 |
| **H1e** | AM → RP | 0.476 | - | - | 6.970 | 0.000 | 0.159 |
| **H2** | AM → SCI | 0.473 | 0.492 | 0.080 | 5.949 | 0.000 | - |
| **H2a** | AM → II | 0.424 | - | - | 5.806 | 0.000 | 0.473 |
| **H2b** | AM → CI | 0.394 | - | - | 5.046 | 0.000 | 0.473 |
| **H2c** | AM → SI | 0.424 | - | - | 5.698 | 0.000 | 0.473 |
| **H3** | SCI → SCP | 0.300 | 0.289 | 0.146 | 2.049 | 0.041 | - |
| **H3a** | SCI → SOP | 0.250 | - | - | 2.001 | 0.046 | 0.300 |
| **H3b** | SCI → COP | 0.255 | - | - | 1.975 | 0.049 | 0.300 |
| **H3c** | SCI → CCP | 0.182 | - | - | 1.833 | 0.067 | 0.300 |
| **H3d** | SCI → TBP | 0.218 | - | - | 2.007 | 0.045 | 0.300 |
| **H3e** | SCI → RP | 0.255 | - | - | 2.006 | 0.045 | 0.300 |
| **H4** | SCP → FP | 0.456 | 0.463 | 0.090 | 5.065 | 0.000 | - |

Legend: AM = Additive Manufacturing adoption; CCP = cost-containment performance; CI = customer integration; COP = customer-oriented performance; FP = firm performance; II = internal integration; RP = reliability performance; SCI = supply chain integration; SCP = supply chain performance; SI = supplier integration; SOP = supplier-oriented performance; TBP = time-based performance

Furthermore, supply chain integration has positive and statistically considerable influence on automotive supply chain performance ($\beta$=0.300, $p$<0.05). Therefore, H3 is supported. When considering the influence of supply chain integration on each supply chain performance dimension, one can conclude that supply chain integration has positive and statistically considerable influence on each supply chain performance dimension ($p$<0.05), except for the cost-containment performance (not statistically significant influence, $p$>0.05). Accordingly, the third set of hypotheses H3a-H3e of this research is also accepted.

Finally, supply chain performance has positive and statistically considerable influence on firm performance in automotive industry ($\beta$=0.456, $p$<0.001), meaning that H4 is supported. Thus, the *t*-value, *p*-value results and all bootstrap confidence intervals that do not include value 0 (Table 6) indicate that all indirect relations show a considerable level of influence, which means accepting all sub-hypotheses, except for the cost-containment performance which has a statistically insignificant influence (0.182, $t$=1.833, $p$>0.05).

## 5. Discussion

### *5.1. Overview*

The results of this study highlight some interesting new findings for Additive Manufacturing, providing evidence for its potential impact on supply chain integration and performance. The data presented in this study show that H1 and H3c are partially supported, whilst all other hypotheses are fully supported.

For H1 it is shown that Additive Manufacturing adoption has the strongest influence on customer-oriented performance and reliability performance (i.e. loading factor 0.476), but the weakest influence on cost-containment performance (i.e. loading factor 0.341). Hence, Additive Manufacturing may allow automotive companies to satisfy their customers through the responsive fulfillment of new and existing products, whilst maintaining high service levels and effective management of inventory. However, these valuable capabilities do come with the financial penalty arising from Additive Manufacturing. It is well-established that the technologies are cost-competitive for low production volumes (e.g. Mellor *et al.*, 2014; Ruffo and Hague, 2008); typically, automotive parts are produced in relatively high volumes, for which Additive Manufacturing is far less competitive.

For H2 we find Additive Manufacturing has the strongest influence on supplier integration and internal integration (i.e. loading factor 0.424) but has the weakest influence on customer integration (i.e. loading factor 0.394). In the automotive context we recognize the relatively tight integration between companies in the supply chain engaged in collaborative research and development activities that yield new products, which are activities that the digital nature of Additive Manufacturing has previously been shown to support. The corresponding lack of customer integration could be considered a temporal issue; we note that currently few customers are actively involved with the design of their automobile that necessitates new or altered products being made. Currently, most buyers are satisfied by the selection of modules from a variety of options, rather than designing their own. There are already some exceptions; notably 3D printing has been used for several years in the high-end luxury car market, allowing customers to design elements of their own car such as dash panels and door handles. In the future several new initiatives such as "Hackrod" (http://hackrod.com/) seek to redefine the design and manufacture of vehicles, engaging the consumer as a co-creator of their own vehicle. Such co-creation effectively engages the customer in the New Product Design activities traditionally managed by the manufacturer, and the complexity of the work to be undertaken is likely to necessitate a much stronger integration with the customer.

In H3 we identify that our findings are consistent with the seminal papers of Frohlich and Westbrook (2001) and Huo (2012) in confirming the connection between high levels of integration within the supply chain and corresponding levels of performance. The sub-hypotheses analysis (H3a-H3e) showed that from all supply chain performance dimensions, supply chain integration has the greatest effect on customer-oriented and reliability performance (i.e. loading factor 0.255), underlining the importance of fulfilling customer requirements is a priority within the automotive industry.

Finally, in H4 we identify that firm performance is a consequence of the performance achieved within the supply chain, underlining the importance of effective supply chain management for the automotive industry. Our findings here echo more general observations by Hakansson and Prenkert (2004) who have shown that effectiveness is a direct consequence of supply chain management efficiency.

### *5.2. Research implications*

There have been multiple calls for more research on how Additive Manufacturing affects the supply chain (e.g. Potter *et al.*, 2015; Waller and Fawcett, 2014), and this has often been motivated by expectations of the radical change that may result from the adoption of the technologies. Whilst an increasing number of researchers are beginning to work in this area, there is still a distinct lack of quantitative research that is informed by industry practice but underpinned by rigorous supply chain management theory. Therefore, in proposing and testing direct relations within the model, the emphasis is put on Additive Manufacturing as a promising technology enabling enormous changes for supply chains (e.g. Candi and Beltagui, 2019; Christopher and Ryals, 2014; Waller and Fawcett, 2014) and supply chain management dimensions (supply chain integration and performance). This work aims to provide some closure to the research gap by providing a detailed quantitative evaluation that draws on appropriate supply chain management literature in its development, informed by a representative industry sample.

Our results support the view that Additive Manufacturing can make a positive contribution for the supply chain, but this is not achieved by the machines in isolation. Many of the 'traditional' activities of supply chain management are still needed when employing Additive Manufacturing, and further research is needed to understand whether Additive Manufacturing adoption will necessitate changes to the way these traditional activities are undertaken. Considering the low statistical influence of Additive Manufacturing adoption on automotive supply chain performance, it is identified that individual Additive Manufacturing technologies are not themselves a source of competitive advantage: they need to be effectively incorporated within the supply chain (i.e. supply chain integration) to be effective. As the results show strong statistical influence of Additive Manufacturing adoption on supply chain integration and consequently on supply chain performance, our findings suggest companies will gain competitive advantage only when Additive Manufacturing is integrated with core capabilities such as strong relationships with supply chain members. This is a particularly interesting observation, since it suggests some of the existing assumptions that Additive Manufacturing will positively affect the supply chain through its simplification may be overoptimistic.

For automotive supply chains which are typically both complex and extensive, the assumption that any individual process technology will allow manufacturers to divest of swathes of its supply chain within the near-term is probably somewhat reaching. Some disintermediation of the supply chain may occur, but research is needed to understand how and why this may arise. Currently we observe a trend for automotive firms to increase their focus on closer relationships with strategic suppliers to exploit their specialist capabilities; for example, car manufacturers partnering with information technology providers to develop in-car navigation and infotainment systems. Well-managed relationships in the automotive supply chain can support greater knowledge generation and transfer than may be achieved by a single firm (Dyer and Nobeoka, 2000), and so where the application of Additive Manufacturing supports supply chain integration, we might expect to find a corresponding improvement in supply chain performance. In such circumstances the benefits to manufacturers arises from improving the contributions provided by entities in the supply chain, rather than simply reducing their numbers.

Additionally, the research finds that customer integration is currently relatively weak, but this is something that will need to improve for those companies attempting a customer co-design and co-creation agenda. Building on the findings of the current study, more work is therefore needed to understand how operations within the supply chain may be changed, and how this may affect both the integration and performance of the supply chain.

### *5.3. Practical implications*

The capabilities of Additive Manufacturing are well established in both research and practice, and our survey underlines that Additive Manufacturing has been adopted within companies of all sizes and roles within the automotive supply chain. However, whilst Additive Manufacturing can allow practitioners to make new products in new ways, this type of differentiation will not ensure a sustained competitive advantage is maintained (Powell and Dent-Micallef, 1997). Within this work we have therefore focused on the concepts of supply chain integration and performance that do offer long-term benefits for firms, and which are not as easily replicated as the introduction of new ‘off-the-shelf’ technologies.

Within H1 we show the benefits of Additive Manufacturing for customer service and reliability performance, but note that this comes at a financial cost. This would suggest that companies need to think carefully about which products Additive Manufacturing technologies are best suited for, rather than blindly applying them across the entire product range: just because you can with Additive Manufacturing does not mean you should! Companies should therefore prioritize those products which customers most value the service benefits, and where cost sensitivity is lessened. For example, studies in aerospace (e.g. Khajavi *et al.*, 2014) have already suggested benefits arising from quick response and lessened inventory in the supply of spare parts. Whilst mainstream automotive spare parts for current models are likely to be demanded in volume, much opportunity may exist for older vehicles legacy spare parts no long supported by the OEM. Such products still require the rapid response and high service levels, but the increased costs may compare favorably to low volume production of otherwise obsolete parts using conventional technologies.

Additionally, in H2 we show that integration between suppliers is relatively good when compared to customers. There is, therefore, an opportunity to enhance customer integration and automotive companies may find this beneficial for their operations, particularly if there is an appetite for engaging the customer in co-design to increase the overall value proposition and competitiveness of the offering. Already the internet has been widely recommended for co-creation with Additive Manufacturing (Rayna *et al.*, 2015), however the interface between customers and manufacturers is often very complex (Berger *et al.*, 2005), and the practical challenge of integrating the customer in what is often a short-term transactional relationship may be difficult to achieve. Taken together, H1 and H2 support the achievement of increased performance within both the supply chain (H3) and individual firms (H4), underlining the benefits of these capabilities.

We suggest the findings of this study offer considerable benefit for those companies considering the adoption of Additive Manufacturing, and may serve as a valuable insight in the strategic decision-making process. For those already using Additive Manufacturing, this study serves to underline that they may expect their investment to yield improvements to firm performance. Using our framework (Figure 1), we argue that the potential exists for firms to focus on improvements to their production strategies and policies.

## 6. Conclusion

The aim of this paper was to examine Additive Manufacturing adoption and its associated variables in the supply chain context. Special attention is given to the intermediate effect of supply chain integration on the relationship between Additive Manufacturing adoption and supply chain performance. The model was defined after systematic analysis of the Additive Manufacturing adoption concept and different dimensions of supply chain management, with great attention dedicated to the specificity and legality of the automotive industry. Based on available literature in the field of Additive Manufacturing, supply chain management and related factors, and opinions of experts from the logistics management and automotive industry, a theoretical model was designed and tested on automotive OEMs and suppliers. The objective of the proposed model was to analyze the contribution of Additive Manufacturing in production processes to the efficiency and effectiveness of the automotive supply chain management. Two supply chain management factors were identified (supply chain integration and supply chain performance), through which the ability to optimize the supply chain was tested. Empirical research has given the answer to proposed research question: building on RBV, Additive Manufacturing adoption positively affects automotive supply chain performance and consequently firm performance, whereby supply chain integration indirectly supports performance improvements enabled by Additive Manufacturing adoption. Based on these results, the paper provides rich insights for both managers and researchers to successfully adopt Additive Manufacturing in the context of automotive supply chain management, though we recommend further studies are necessary to provide corroboration of these findings in other industrial contexts. One particularly interesting line of enquiry would be to explore how Additive Manufacturing affects firm performance. In the current study we have focused our attention on the supply chain, but future work may wish to examine this concept in detail at the individual firm level.

## Appendix 1

### Table 7 Construct measurement summary

| Indicator | Item description | Factor loading | Cronbach alpha value | Average variance extracted | Composite reliability |
|---|---|---|---|---|---|
| **Additive Manufacturing adoption** | Please rate the extent of application of the following technological tools in your company to support AM adoption (1-very low; 5-very high): | - | **.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 | - | - | - |
| **Additive Manufacturing adoption** | Please rate to what extent do you disagree or agree with the stated claims regarding the level of AM adoption in your company: | - | - | - | - |
| 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 integration** | Your company may be involved in multiple supply chains and have multiple suppliers and customers; please consider only those where your company has implemented Additive Manufacturing. This part of the questionnaire focuses on the integration of your supply chain. | - | - | - | - |
| ***Internal integration*** | Please rate the extent of integration in the following areas (1-very low; 5-very high): | - | **.857** | **.579** | **.892** |
| SCI_II1 | Integrated inventory management systems | x | x | x | x |
| SCI_II2 | Integrated logistics support systems | .767 | - | - | - |
| SCI_II3 | Inter-functional data sharing | .707 | - | - | - |
| SCI_II4 | The use of cross functional teams in process improvement | .780 | - | - | - |
| SCI_II5 | The use of cross functional teams in new product development | .793 | - | - | - |
| SCI_II6 | The utilization of periodic interdepartmental meetings among internal functions | .762 | - | - | - |
| SCI_II7 | Real-time searching of the level of inventory | x | x | x | x |
| SCI_II8 | Real-time integration and connection among all internal functions in company | .753 | - | - | - |
| ***Customer integration*** | Please rate the extent of integration or information sharing between your company and these customers in the following areas (1-very low; 5-very high): | - | **.788** | **.521** | **.844** |
| SCI_CI1 | Our company has a convenient ordering system for these customers | .753 | - | - | - |
| SCI_CI2 | Our company shares production plans | .743 | - | - | - |

| | | | | | |
|---|---|---|---|---|---|
| | with these customers | | | | |
| SCI_CI3 | Our company has regular communication with these customers | x | x | x | x |
| SCI_CI4 | These customers give us feedback about our products | x | x | x | x |
| SCI_CI5 | These customers share market information with our company | .671 | - | - | - |
| SCI_CI6 | These customers provide inputs for our production planning processes | .699 | - | - | - |
| SCI_CI7 | These customers participate in product development processes | .738 | - | - | - |
| ***Supplier integration*** | Please rate the extent of integration or information sharing between your company and these suppliers in the following areas (1-very low; 5-very high): | - | **.844** | **.519** | **.882** |
| SCI_SI1 | These suppliers participate in our production planning processes | .758 | - | - | - |
| SCI_SI2 | These suppliers participate in design stage of product development | .634 | - | - | - |
| SCI_SI3 | These suppliers participate in our procurement processes | .670 | - | - | - |
| SCI_SI4 | These suppliers share their production schedule with us | .811 | - | - | - |
| SCI_SI5 | Our company exchanges information with these suppliers | .625 | - | - | - |
| SCI_SI6 | Our company has an automated ordering system with these suppliers | .808 | - | - | - |
| SCI_SI7 | Our company has a stable procurement relationship with these suppliers | .713 | - | - | - |
| **Supply chain performance** | Your company may be involved in multiple supply chains and have multiple suppliers and customers; please consider only those where your company has implemented Additive Manufacturing. This part of the questionnaire focuses on the performance of your supply chain. | - | - | - | - |
| ***Customer-oriented performance*** | Please rate the extent to which you disagree or agree to the following statements concerning your supply chain performance with respect to these customers (1-strongly disagree; 5-strongly agree): | - | **.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*** | Please rate the extent to which you disagree or agree to the following statements concerning your supply | - | **.866** | **.734** | **.892** |

| | | | | | |
|---|---|---|---|---|---|
| | chain performance with respect to these suppliers (1-strongly disagree; 5-strongly agree): | | | | |
| 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 outstanding on-time delivery record to our supply chain | x | x | x | x |
| 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*** | Please rate the extent to which you disagree or agree to the following statements regarding your supply chain cost performance (1-strongly disagree; 5-strongly agree): | - | **.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*** | Please rate the extent to which you disagree or agree to the following statements regarding your supply chain reliability performance (1-strongly disagree; 5-strongly agree): | - | **.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*** | Please rate the extent to which you disagree or agree to the following statements regarding your supply chain time-based performance (1-strongly disagree; 5-strongly agree): | - | **.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 | - | - | - |

| | | | | | |
|---|---|---|---|---|---|
| **Firm performance** | Please evaluate your company's performance in the following areas relative to your major competitors (1-very low; 5-very high): | - | **.918** | **.637** | **.933** |
| FP1 | Market share | .688 | - | - | - |
| FP2 | Growth in market share | .740 | - | - | - |
| FP3 | Growth in sales | .739 | - | - | - |
| FP4 | Growth in profit | .793 | - | - | - |
| FP5 | ROI | .814 | - | - | - |
| FP6 | Growth in ROI | .858 | - | - | - |
| FP7 | ROS | .869 | - | - | - |
| FP8 | Growth in return on sales | .861 | - | - | - |

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

Legend: AM = Additive Manufacturing adoption; CCP = cost-containment performance; CI = customer integration; COP = customer-oriented performance; FP = firm performance; II = internal integration; RP = reliability performance; SCI = supply chain integration; SCP = supply chain performance; SI = supplier integration; SOP = supplier-oriented performance; TBP = time-based performance

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