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Path to Improved Supply Chain Performance: Additive Manufacturing Adoption, Integration, and Responsiveness

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Abstract

Purpose: This study aimed to empirically investigate how additive manufacturing (AM) adoption affects supply chain performance (SCP) through supply chain integration (SCI) and responsiveness. **Research and Design Methodology:** This study adopted a quantitative research design; data were collected via a survey that targeted a sample of firms that have adopted specific AM technologies. The survey measured AM adoption readiness, SCI, agility, and performance. This study employs structural equation modeling to test the hypothesized relationships among these variables while accounting for firm size, industry, and supply chain complexity. To validate the structural equation model, we utilized 195 survey responses collected from employees working in supply chain-related departments in Korea. Furthermore, we would like to state that SPSS 18.0 and AMOS 18.0 were used for the statistical analysis. **Principal Results:** Our empirical findings support all four hypotheses, indicating that a higher level of AM adoption stimulates SCI and complementary supply chain responsiveness requirements. The results indicate that AM adoption can improve SCP through the integration and responsiveness. **Conclusions:** This study contributes to the growing body of knowledge on the strategic implications of AM for supply chain management. The findings highlight the importance of considering AM as a strategic enabler of SCP rather than solely a tactical tool.

Keywords: Additive Manufacturing Adoption, Supply Chain Integration, Supply Chain Responsiveness, Supply Chain Performance

JEL Classification Code: M00, M10, M11

1. Introduction

Constantly rising global competition, growing customer expectations, and changing demands from customers' pressure organizations to improve their supply chain performance (SCP). Currently, the ability to deliver products quickly and efficiently (and cost-effectively) is often a matter of business life or death (Min et al., 2019). In this context, additive manufacturing (AM) or 3D printing represents a disruptive technology that could potentially revolutionize how supply chain management (SCM) is implemented (Beltagui et al., 2023). Incorporating supply chain integration (SCI) and responsiveness as mediators to investigate the impact of AM adoption on SCP.

AM is the process of creating objects from digital 3D designs and building them layer-on-layer using materials that include polymers, metals, and ceramics (Prashar et al., 2023). This technology can provide numerous benefits over conventional manufacturing, such as freedom of design, speed of prototyping, and the possibility of on-site

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production. AM has the capacity to transform our current design, product development, production, and distribution workflows through new capabilities, such as 3D printing of parts with complex geometries that are difficult (or impossible) to manufacture using subtractive techniques or whose tooling setup requires a costly long time, such as injection-molded parts (Beltagui et al., 2020). However, empirical studies investigating the impact of AM on the overall SCP remain scarce in the study of AM.

Hence, the current study suggests that organizations' adoption of AM by organizations might be used to enhance performance in their supply chain, and this relationship is likely tempered or enforced through SCI and responsiveness. It entails the integration of processes, technologies, and systems across organizational boundaries to enable a smooth and continuous flow or supply of goods or services from order to delivery (Adeitan et al., 2021). SCI is essential in the context of AM because it permits the connection between digital design data, material flows, and production schedules within an entire supply chain (Richey et al., 2022). This study finds that the integration of supply chains needs to enable benefits from AM to be optimized and improvements generated in SCP.

Supply chain responsiveness (SCR) refers to how quickly and effectively market changes, demand requirements, or instances of supply chain disruptions can be dealt with (Handfield & Bechtel, 2002). This includes the ability to identify, understand, and respond to constantly shifting market signals as well as rapid scalability when it comes to production levels, product mix, or delivery schedules. AM can only produce tailored products when needed, making its capacity to meet supply chain demands more responsive. With additive technology, companies can develop new products more rapidly and get them to market faster with shorter lead times for greater product customization (Vinodh et al., 2009).

Previous research has primarily focused on the technical and operational aspects of AM, such as rapid prototyping and design flexibility (Lee et al., 2005). However, there is a notable lack of studies examining the structural relationships between AM adoption and broader supply chain metrics such as SCI, SCR, and SCP. This study investigates the relationships among AM adoption, SCI, SCR, and SCP through a thorough literature review and empirical analysis. By examining these relationships, this study aims to provide a richer understanding of how organizations can utilize AM technologies to enhance their SCP. Therefore, this study aims to address this gap by expanding insights into the emerging research area of AM within SCM. It is expected to provide managerial implications for practitioners considering the adoption of this technology in their supply chain operations.

2. Literature Review

2.1. Additive manufacturing adoption

3D stereo lithography, also known as AM or 3D printing, simultaneously creates physical objects in one layer of material from a digital 3D model (Mukhtarkhanov et al., 2020). Over the last few years, this technology has received considerable attention because it can significantly obliterate traditional manufacturing and supply chain exercises. The level at which an organization integrates 3D printing technologies into its production and supply chain activities defines the degree of AM adoption (Schniederjans, 2017).

The characteristics of AM adoption, regarding breadth and depth, how far an organization has invested in its 3D printing infrastructure, or organizational readiness, amounts to a multidimensional construct (Rylands et al., 2016). Breadth of adoption describes the range of products/materials/applications for which AM is used, whereas the depth of adoption refers to the extent to which 3D printing will be integrated across core production processes within a firm (Candi & Beltagui, 2019). AM infrastructure investment entails owning 3D printers, software, people who know how to run them, and the execution of policies and processes that underpin AM. Preparedness includes a whole basket of things, from support at the top to training employees right through where AM fits into the broader strategic plan for your business (Bhardwaj et al., 2019).

Several theories explain AM in the supply chain. The technology acceptance model posits that the perceived usefulness and ease of use of a new technology are important predictors of its uptake (Oettmeier & Hofmann, 2017). In the case of AM, usefulness can be related to aspects such as design flexibility, quick prototyping speed, reduced tooling costs, ease of use, and the availability and simplicity of user-friendly 3D printing software (Ngo et al., 2018). According to the diffusion of innovation theory, a new technology is adopted when it offers relative advantage, higher compatibility, lower complexity, trainability, and observability (Marak et al., 2018). Examples of the relative advantages of AM include the ability to produce complex geometries, mass-customization benefits, and reduction of waste and inventory costs. The measures employed here can also be categorized as compatibility and complexity. Compatibility is the way in which 3D printing fits with an organization's other processes, norms, and objectives, whereas complexity concerns how difficult it is to implement and use this technology (Schniederjans, 2017).

This is known as the resource-based view (RBV), which argues that a bundle of resources and capabilities creates a competitive advantage for an organization (Delic et al., 2019). For AM, resources may include 3D printing equipment and materials or expertise; simultaneously, capabilities can refer to design capabilities and process knowledge. From an RBV perspective, organizations that can successfully combine their AM resources and capabilities will be more successful in achieving higher-level performance outcomes (Chaudhuri et al., 2022).

Existing research on additive manufacturing (AM) has predominantly focused on its technical and operational aspects. However, there is a notable paucity of studies examining the structural relationships between AM adoption and broader supply chain metrics such as supply chain integration (SCI), supply chain responsiveness (SCR), and supply chain performance (SCP). Therefore, this study aims to address this gap by investigating the significance of AM adoption in supply chain enterprises and its impact on these critical supply chain metrics.

2.2. Supply Chain Integration

The extent to which organizations coordinate and collaborate with their supply chain partners determines the SCI level they have achieved (Power, 2005). The alignment and synchronization of processes, systems, and decisions across the supply chain generates value for customers and stakeholders: SCI with a multidimensional view that includes internal, supplier, and customer integration (Wong et al., 2013).

Internal integration refers to the level of cooperation and coordination across various functional units within an organization, such as sourcing, manufacturing, distribution, and marketing (Zhu et al., 2018). It no longer includes organizational silos, sharing of information and resources between departments involved in product delivery, and the alignment of goals and metrics across organizations. Smooth operation of inbuilt systems finding solutions for customer demands and supply chain efficiency means internal integration (Esan et al., 2024).

Different theories are used to explain the terms SCI. According to resource dependence theory, organizations require resources that they cannot completely control and, hence, must establish inter-organizational linkages to reduce uncertainty in their environment and manage dependencies (Kim et al., 2020). At a more operational level, firms with tight SCI may develop partnerships and collaboratively work as joint stakeholders, similar to shared ventures through intermediaries (vendors) or suppliers (Perdana et al., 2020). The theory of transaction cost economics predicts that organizations will always seek to reduce the costs associated with transactions such as search, negotiation, and monitoring. This leads to three scale advantages: trust, commitment, and relational governance with supply chain partners, from which SCI can reduce transaction costs (Wever et al., 2012).

Research on supplier-enabled value (SEV) adopted a standpoint developed by the relational view of relations between organizations, but a competitive advantage is created by connecting complementary resources and capabilities (Chen et al., 2013). Regarding SCI, channel partnerships with customers and suppliers can create distinctive resources and capabilities through joint product development process improvements and knowledge sharing (Mofokeng & Chinomona, 2019).

Furthermore, integrated supply chains can help businesses take advantage of the agility and responsiveness offered by AM when faced with varying customer demands or market conditions (Shukor et al., 2021). In addition to the spread of the economy, companies can rapidly change the way they design, produce, and deliver internally or with customers and suppliers (Porter & Heppelmann, 2014). Incorporating SCI could also promote knowledge transfer and best practices in AM so that organizations can gradually build up their 3D printing expertise to overcome technical and organizational challenges (Chan et al., 2018).

Therefore, SCI is an essential element for effectively integrating AM adoption. This integration offers numerous benefits, including operational cost reduction and the attainment of competitive advantage. Consequently, SCI is indispensable in modern supply chain strategies.

2.3. Supply Chain Responsiveness

SCR is the ability to respond quickly and effectively to unpredictable changes in demand. Market conditions and supply chain disruptions are driven by self-imposed problems or shocks (Ng & Ahmed, 2024). This includes the ability to detect, interpret, and respond to changes in market signals as well as flexibility in the volume of production required for products featured on shelves and when these need to be delivered (Giannakis et al., 2019). The rate at which new resources are made accessible is crucial than ever before, something that a fleet economy can achieve to unlock peak competitiveness in the recent business world.

A responsive supply chain is related to agile manufacturing, which refers to flexibility in supplying the needs of customers quickly with high velocity and adaptability (Fayezi et al., 2017). An agile supply chain is built to adapt efficiently to volatile demand changes and supply disruptions without compromising quality or cost inefficiencies (Swafford et al., 2008). Depending on the context, the key dimensions of agility include market sensitivity, response to volatility (response to customer demand), responsiveness/customer focus, flexibility/virtual integration with trading partners, and supply chain scope/fit between processes (Chiang et al., 2012).

Several theories have been proposed to explain SCR. Dynamic capabilities theory suggests that organizations need to develop and deploy specific capabilities to sense, seize, and transform market opportunities and threats (Chowdhury & Quaddus, 2017). In the context of SCR, dynamic capabilities may include the ability to gather and interpret market intelligence, the flexibility to reconfigure supply chain resources and processes, and the agility to respond quickly to changing customer needs. Information processing theory posits that organizations must match their information processing capabilities with the level of uncertainty and complexity in their environment (Srinivasan & Swink, 2018). SCR may require the development of advanced information systems and analytic capabilities to process large volumes of data from multiple sources and support real-time decision-making.

Notably, the disconnection between upstream supply chains and responsiveness has been widely speculated to limit the benefits of 3D printing technology while scaling its integration (Holmström & Partanen, 2014). Manufacturers can use AM to create custom parts as needed, with faster turnaround times and lower inventory holding costs than traditional methods. AM is flexible and agile, allowing companies to respond to changing customer desires and market conditions without tooling costs or long production runs (Reichwein et al., 2020).

Therefore, while traditional supply chain strategies provide a certain level of responsiveness, the adoption of additive manufacturing (AM) can significantly enhance supply chain responsiveness (SCR). In today's uncertain business environment, the importance of SCR is increasingly critical, making it an essential element in effective supply chain management.

2.4. Supply Chain Performance

SCP is the summary measure of the effectiveness and efficiency of an organization’s supply chain, according to the support of strategic goals and objectives (Beamon, 1999). This includes understanding the magnitude of each of these elements, such as metrics-driven closures, and the measurement and evaluation of different aspects of supply chain operations’ decisions and actions is supposedly spur. SCP is an essential function of an organization to meet customer and stakeholder needs, as well as to remain competitive against other organizations in this cutthroat market (Gunasekaran et al., 2004).

The notion of SCP has transformed in response to these changes and the growing complexity of the global business environment (Caniato et al., 2013). Thus, the traditional performance measurements of cost and productivity have been supplemented with a more comprehensive view that incorporates the strategic, tactical, and operational dimensions of SCP. For instance, the balanced scorecard method places greater emphasis on benchmarking performance across four primary dimensions: financial, customer, internal business processes, and learning the straight uphill closing gate of a supply chain (Agami et al., 2012).

Various factors are expected to impact SCP in the adoption of AM. First, AM has the capability to meet supply chain requirements for customization and complexity from any locations especially with shorter lead time—low or zero inventory situation thus reducing waste (Alogla et al., 2021). AM flexibility and the speed of response to different customer requirements or changes in market conditions can achieve this, while lowering cost structures and enhancing quality further (Kulkarni et al., 2021).

Second, successful AM adoption may hinge on organizing the integration and alignment of a number of supply chain processes (i.e., Design → Procurement → Production → Logistics). Combining AM with the surrounding supply chain processes and systems is a big deal in unlocking high performance for companies (Verboeket & Krikke, 2019). Additively manufactured parts are incorporated throughout the value chain from product development to final delivery.

Third, transformation to AM means that a firm must build new skills and understanding of 3D printer technology, material science, and processing (Liu et al., 2018). Greater performance outcomes are more often achieved in organizations that can acquire, share, and apply AM knowledge effectively. Organizations using AM can evolve their capabilities and respond to market dynamics in such a way that those reliant on traditional processes may struggle to emulate through supply chain learning and innovation (Luomaranta & Martinsuo, 2020).

Therefore, moving toward AM may necessitate organizations to have even more responsive supply chains that can adapt rapidly to changes between supply and demand (Arbabian, 2022). This will help companies easily use the flexibility and personalization features of AM while reducing lead times and ensuring higher customer service levels. Organizations that achieve high SCP can effectively balance the trade-offs between cost, quality, and responsiveness (Altekin & Bukchin, 2022).

3. Hypothesis Development

3.1. Additive Manufacturing Adoption and Supply Chain Integration

AM, or 3D printing, could completely warp our view on SCM; crafting custom-engineered and more simplistic products quicker than one can say “last-generation armament factory.” However, implementing technology successfully also means integrating and aligning different supply chain processes, such as designing, purchasing, production, and distribution (Delic et al., 2019).

SCI is the completion that exists between an organization and its supply chain partners, and the extent to which that organization coordinates with its partners to ensure that optimal processes are devised (Thomas, 2016). It is the deliberate coordination and alignment of product design, production processes, resource planning, and analysis capabilities with the corporate direction to create value for customers or stakeholders (Co & Barro, 2009).

AM and other transformative technologies are likely to require greater levels of SCI as part of the process involves sharing digital design files, material specifications, and production schedules among supply chain partners (Attaran, 2017). Additionally, AM utilizes a mix of technology—3D printers, software, and scanners—from different vendors/software service providers as long as they share the same industry-standard file format (thus, it is not an end-to-end solution/asset) (Martinsuo & Luomaranta, 2018).

Additionally, new supply chain collaboration and innovation models, such as co-creating products with customers and suppliers, offering 3D printing capacity in a plethora of ways, and discovering fresh business model/value proposition combinations can be made possible through AM (Thomas, 2016). To achieve this, goals, metrics, and incentives must be integrated and aligned across the supply chain, and trust among partners must be verified alongside long-term relationships (Zhang & Huo, 2013).

Several studies suggested a positive relationship between AM adoption and SCI. For example, Luomaranta and Martinsuo (2020) found that the implementation of AM in supply chains requires the integration of internal processes, such as product development and production, as well as external processes, such as supplier and customer collaboration. Similarly, Arbabian (2022) argued that successful AM adoption depends on the ability to integrate and coordinate various supply chain functions such as procurement, logistics, and quality management.

Based on these arguments and findings, we propose the following hypothesis:
H1: AM adoption positively influences SCI.

3.2. Additive Manufacturing Adoption and Supply Chain Responsiveness

Furthermore, AM adoption is expected to impact SCR and SCI. The response capacity of a supply chain refers to an organization and its partners' ability to cope with these changes by swiftly readjusting to new customer demands, market opportunities, or supply setbacks (Ayoub & Abdallah, 2019). Industry 4.0, which has the capacity to sense, interpret, and act on dynamic market signals, shapes decisions regarding production volumes, product mix, and delivery schedules quickly (Chowdhury & Quaddus, 2017).

AM can increase SCR by producing custom products in short production times with lower inventory levels per item compared with traditional manufacturing methods. The adaptability and responsiveness of AM allow companies to react rapidly as customer demand shifts or market conditions change, without incurring the costs of expensive tooling or high-volume production runs (Naghshineh & Carvalho, 2022).

The decentralized distribution of AM can help firms place production closer to customers while saving transportation costs and reducing delivery time. This enables manufacturers to create highly responsive supply chains with rapid response capabilities by coalescing AM capabilities within their standard supply chain operations, such as demand forecasting and logistics (Velázquez et al., 2020).

Several studies have suggested a positive relationship between AM adoption and SCR. For example, Delic and Eyers (2020) found that AM can improve SCR by reducing lead times, increasing flexibility, and enabling mass customization. Similarly, Thomas (2016) argued that AM can help organizations respond quickly to changing customer needs and market conditions while also reducing costs and improving quality.

Based on these arguments and findings, we propose the following hypothesis:
H2: AM adoption positively influences SCR.

3.3. Supply Chain Integration and Supply Chain Performance

SCI is hypothesized to have a positive effect on SCP. SCP is a measure of how effectively and efficiently an organization's supply network functions to achieve its strategic objectives (Fabbe-Costes & Jahre, 2008). This includes the measurement and definition of issues as part of the supply chain function, such as cost, quality, delivery, flexibility, and innovation.

SCI refers to the systematic relationship and synchronization of processes, resources, data, and planning over the supply chain to secure deliverables for customers as well as stakeholders' benefits (Dainty et al., 2001). It provides a way to collaborate and integrate your organization with your supply chain partners so that goods, delivery, or services and information flow properly among the companies (and perhaps their suppliers too) for efficient and effective delivery of products and/or services.

Several studies have suggested a positive relationship between SCI and SCP. For example, Gimenez et al. (2012) found that SCI, including internal, customer, and supplier integration, has a positive impact on operational and business performance. Similarly, Kim (2013) found that SCI enhances the positive effects of SCM practices on operational performance.

Various factors may explain why SCI leads to better SCP. First, Huo et al. (2014) found that SCI enables organizations to reduce costs and inefficiencies by eliminating duplication and waste, streamlining operations, and achieving economies of scale. Second, supply chain integrated quality and reliability are improved by a standardized, consistent, and coordinated flow of material information and finances through the supply chain. Third, SCI enhances flexibility and responsiveness in adapting to changes in customer demand and market, as organizations can act quickly.

Based on these arguments and findings, we propose the following hypothesis:
H3: SCI positively influences SCP.

3.4. Supply Chain Responsiveness and Supply Chain Performance

SCR is expected to play a significant role in improving SCP. SCR is the speed and effectiveness of a supply chain in response to changes in the market, customer demand, or business models, with appropriate return on investment opportunities (Handfield & Bechtel, 2002). This includes the ability to reliably detect, understand, and respond to real-time signals from the market as well as to modulate production volume, product mix, and delivery schedules on the fly.

By contrast, SCP refers to how well a supply chain meets an organization's strategic goals and objectives. It consists of measuring and assessing several characteristics of supply chain operations such as costs and quality of customer service (Gunasekaran et al., 2004).

Several studies have suggested a positive relationship between SCR and SCP. For example, Gligor et al. (2015) found that SCR positively impacts SCP, as it enables organizations to quickly adapt to changes in customer needs and market conditions. Similarly, Blome et al. (2013) found that SCR enhances the positive effects of supply chain agility on operational performance.

First, SCR directly impacts supply performance for several reasons for its positive effect. Eckstein et al. (2015) found that SCR can allow companies to reduce lead times and speed of deliveries, which in turn increases customer satisfaction and loyalty. Second, SCR adds flexibility and agility, allowing organizations to introduce new products quickly, enter new markets, or respond to competitive threats. Third, SCR can reduce costs and streamline operations by reducing inventory levels and obsolescence, thereby producing magnification while maximizing resource use.

Based on these arguments and findings, we propose the following hypothesis:
H4: SCR positively influences SCP.

A research model (Figure 1) was established to test the above hypothesis pertaining to the causal relationships among AM adoption, SCI, SCR, and SCP.

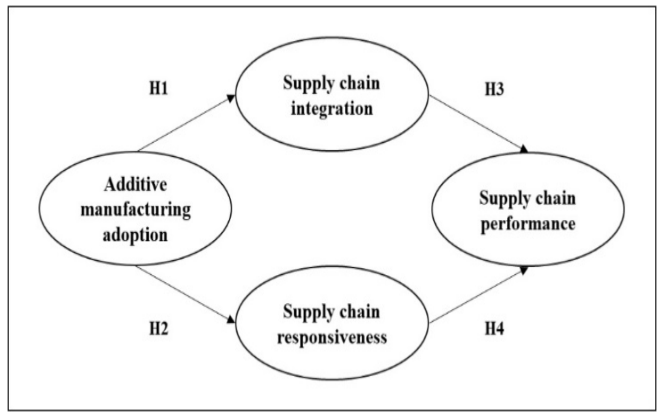

Figure 1: Research model

4. Methods

4.1. Data Collection and Measurement of Variables

To verify these hypotheses, we conducted a survey targeting employees working in supply chain-related departments in South Korea. Before distributing the survey, the researchers sought advice from two practitioners and two professors specializing in production management to ensure the validity of the research content. Based on their advice, we were able to finalize the selection of survey questions, and we distributed the questionnaires. Approximately 1000 questionnaires were distributed over a period of about two weeks, and a total of 195 questionnaires, excluding insincere responses, were ultimately used for statistical analysis. Table 1 presents the survey questions used for measurement in this study.

Table 1: Operational Definitions of Variables

Construct	Item	Reference
AM adoption	Our organization has extensively implemented AM technologies in our production processes.	Oettmeier and Hofmann (2017); Rylands et al. (2016)
	We have invested significant resources (e.g., time, money, and personnel) in AM technologies.	
	AM technologies are well-integrated with our existing manufacturing systems and processes.	
	We have a high level of expertise and knowledge in AM technologies within our organization.	

Construct	Item	Reference
SCI	We actively share information with our supply chain partners to facilitate coordination and decision-making.	Power (2005); Van der Vaart and Van Donk (2008)
	We collaborate closely with our supply chain partners to develop joint strategies and plans.	
	Our processes and systems are well-integrated with those of our supply chain partners.	
	We have strong, long-term relationships with our key supply chain partners.	
SCR	Our supply chain can quickly respond to changes in customer demand and market conditions.	Fayezi et al. (2017); Handfield and Bechtel (2002)
	We have the flexibility to adjust our production volumes and product mix in response to market changes.	
	Our supply chain can rapidly introduce new products and services to meet evolving customer needs.	
	We have the ability to quickly reconfigure our supply chain resources and processes to adapt to disruptions or opportunities.	
SCP	Our supply chain consistently delivers products and services to customers on time and in full.	Arzu Akyuz and Erman Erkan (2010); Beamon (1999)
	We have high levels of customer satisfaction and loyalty due to our SCP.	
	Our supply chain is able to minimize costs while maintaining high levels of quality and service.	
	We have a strong track record of innovation and continuous improvement in our supply chain processes.	

4.2. Reliability and Validity Testing

Before verifying the hypotheses based on the data collected through the survey, we conducted reliability and validity analyses on the data used. First, Cronbach's alpha values were used for the reliability analysis. Generally, in the field of business administration, if the Cronbach's alpha value is at least 0.7, reliability is secured (Hair et al., 2010). All the measurement concepts used in this study had values of 0.7 or higher, indicating that internal consistency was achieved. Subsequently, to verify convergent validity, construct reliability (CR) and average variance extracted (AVE) were calculated. Typically, when the CR value is 0.7 or higher and the AVE value is 0.5, convergent validity is considered secure (Hair et al., 2010). The results showed that convergent validity was achieved in this study. Table 2 presents the findings of the reliability and convergent validity tests and Table 3 shows the goodness-of-fit results of the initial measurement model.

Table 2: Findings of the Reliability and Convergent Validity Tests

	Cronbach's alpha	CR	AVE
AM adoption	0.867	0.866	0.703
SCI	0.925	0.912	0.745
SCR	0.874	0.896	0.712
SCP	0.912	0.904	0.721

Table 3: Goodness-of-fit Results for Initial Measurement Model

CMIN/DF	GFI	AGFI	TLI	CFI	RMSEA
1.289	0.910	0.889	0.960	0.954	0.046

Finally, to determine whether discriminant validity was achieved, we compared the AVE values with the squared correlation coefficients. If the squared correlation coefficient is smaller than the AVE value, discriminant validity can be considered. Discriminant validity was achieved in this study. Table 4 presents the results.

Table 4: Discriminant Validity Test Results

	AM adoption	SCI	SCR	SCP
AM adoption	0.703	-	-	-
SCI	0.502	0.745	-	-
SCR	0.368	0.230	0.712	-
SCP	0.361	0.256	0.298	0.721

* The diagonal represents the AVE values, whereas the other values represent the squared correlation coefficients.

4.3. Empirical analysis

After completing the reliability and validity tests, the fit indices of the structural models were examined. The results are summarized in Table 5. Most indices met the criteria recommended by Hair et al. (2010). Consequently, the hypotheses were tested and the results are presented in Table 6.

Table 5: Fit Indices of the Structural Model

CMIN/DF	GFI	AGFI	TLI	CFI	RMSEA
1.265	0.902	0.878	0.961	0.952	0.045

Table 6: Hypothesis Test Results

Hypothesis	Beta	S.E.	*p*	Result
H1	0.652	0.080	0.000	Adopted
H2	0.274	0.146	0.000	Adopted
H3	0.815	0.127	0.000	Adopted
H4	0.361	0.063	0.000	Adopted

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

5. Discussion

5.1. Conclusion

In the contemporary volatile business landscape, numerous enterprises are fortifying their supply chains to attain competitive advantages. Despite the significant advancements heralded by the Fourth Industrial Revolution, there is a conspicuous paucity of research on additive manufacturing (AM) adoption within the realm of supply chain management. Consequently, this study undertakes an empirical investigation into the effects of AM adoption on supply chain integration (SCI), supply chain responsiveness (SCR), and supply chain performance (SCP) among Korean firms that are actively engaged in supply chain development. The analysis yields the following insights.

H1 is supported (i.e., AM adoption has a direct positive effect on SCI), indicating that the more an organization adopts technologies in AM, the more likely it is to achieve higher levels of SCI. This observation underscores the need to incorporate AM with other facets of supply chain functions, as well as other technologies such as design, procurement, production, and logistics, to support better collaboration and information sharing along the entire supply chain's value generation.

The significance and direction of support for H2 (i.e., AM adoption leads to increased SCR) reveal that adopting additive technologies may provide an organization with a greater likelihood of achieving superior levels of SCR. This also implies that the adaptability and scalability of AM can enable rapid changes in customer demands or market conditions, which would be impossible without significant investment in tooling or large production runs. Customizing products at scale and near-customer production can also positively impact the SCR.

The existing evidence for H3 (i.e., SCI => SCP) corroborates that the benefits from SCI extend beyond the operational and business levels. This implies that organizations that work in an integrated and coordinated manner with their supply chain partners to deal with products, service flows, information, and financial inflows are likely to have better cost efficiency, quality, delivery flexibility, and innovation outcomes.

H4 (i.e., the stronger the SCR, the higher the SCP) suggests the need for the ability to respond effectively and quickly, such as sensing early warning signals in the way customers behave and creating situational adaptation response processes that would enable benefits associated with agility, flexibility, and maneuverability.

Based on these results, firms seeking to realize the benefits of AM need to consider how they can connect this technology with their supply chain context more broadly and develop the agile capabilities required in a fast-moving world to respond rapidly to changing market conditions and customer requirements.

5.2. Implications

The present study has several implications. First, this study concludes that AM adoption should be considered a strategic facilitator of SCP, and not only an operational tool for prototyping or low-volume production. Thus, it is crucial for organizations to consider how this revolutionary, if not disruptive, technology can improve SCI and SCR and have darting implications on the overall performance of their investments along with long-term strategic planning. This suggests that enterprise-wide and strategic framing of AM adoption is necessary, considering the broader implications for supply chain capabilities and outcomes.

Second, the effects of SCI and SCR are supported, implying that firms should possess the capabilities to achieve beneficial outcomes from AM adoption. This suggests that firms must not only invest in the creation of sociotechnical capabilities—developing relational networks, informal and formal information sharing systems, or cooperative processes with contingencies on either side of their supply chain—but also realize AM's agility. Organizations must build trust, create incentives, and develop a culture of continuous improvement and innovation in their supply chain partners.

Third, this study provides counsel to manufacturing organizations when planning or building a blueprint regarding AM by emphasizing cross-functional collaboration, sharing information, and aligning processes in the supply chain. This has consequences as companies may adopt AM in a fragmented way or they have to change all sides to solve this; hence, part of the derived implication is a holistic and integrative approach in adopting AM, which includes considering AM from all functions/processes of the supply chain, such as design, procurement, production, and logistics. Organizations must also include their supply chain partners in the planning and execution of an AM initiative to ensure alignment and maximize performance results.

Fourth, comprehensive implementation of AM solutions in supply chain are poised to revolutionize the structure of supply chains, making de-centralized production models most likely by eliminating the need for huge storage spaces and long-haul transit routes that could redefine how companies would operate their global transacting features or meet market requirements.

Finally, the stronger strategic position of integrating additive manufacturing in supply chains might significantly improve their resilience and agility thus making them more resistant to large disruptions such as global pandemics or natural catastrophes leading potentially to revolutionizing risk management strategies for supply chain management.

5.3. Limitations and Suggestions

Despite its various implications, this study has several limitations. First, generalizability is limited to the sample characteristics (industry, geographic region, size, etc.) indicated in this study. Although the results should be useful for other organizations in similar contexts, they may not be generalizable to the broader population of organizations adopting AM technologies.

Second, there are major problems with common method bias if data on cultivating AM, SCI, SCR, and SCP within the same constructs are collected from a single respondent in each organization. This could inflate the relationships between variables and compromise the veracity of the findings.

Third, as indicated by the results of this study, it is necessary to examine the impact of AM adoption on SCI, SCR, and SCP across various industries. Each industry has unique supply chain characteristics, which can lead to different effects of AM technology. Therefore, future research should analyze the effects of AM adoption within specific industries and identify optimal practices tailored to each sector. This approach will help maximize the benefits of AM adoption and improve supply chain management efficiency across different industrial contexts.

Lastly, future research, also performed on other specifications or additional variables to control for reverse causality and omitted variable bias. And better measurement could also be done with respect to developing and using new or improved measuring tools, methods of collection (as illustrated by the face-to-face interviews), reducing error so that results are more reliable, potentially even valid.

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