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Unveiling the impact of industry 4.0 on supply chain performance: the mediating role of integration and visibility

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ABSTRACT

Industry 4.0 has revolutionised supply chain processes, providing companies with strategic advantages through advanced technologies such as cyber-physical systems, cloud computing, IoT, AI, and big data. This transformation aligns with the pursuit of high-level supply chain performance, achieved through cross-functional collaboration, end-to-end connectivity, real-time asset tracking, and increased decision transparency. However, the quantifiable extent of its influence has remained an open question, particularly in the context of integration and visibility. To address this gap, our research employs an empirical study, revealing that Industry 4.0 indirectly enhances supply chain performance by improving connectivity and integration within and between organisations, as well as enhancing information visibility and decision transparency. This research uncovers a novel sequential mediation by integration and visibility, offering valuable insights for scholars and industry practitioners alike.

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1. Introduction

The advent of Industry 4.0, the fourth industrial revolution, has ushered in a transformative era in the industrial landscape, marked by the introduction of advanced technologies and innovative concepts relevant to value chain organisation (Wiengarten & Longoni, 2015). This revolution is epitomised by the seamless connectivity of machines, extending into the realm of virtual reality through cutting-edge information technologies (IT) such as cyber-physical systems (CPS), artificial intelligence (AI), big data, Internet of Things (IoT), cloud computing, etc. These technological marvels not only monitor physical processes, but also create virtual representations of the physical world while decentralising decision making in the modular and smart factories in the context of Industry 4.0. As a strategic move, the adoption of Industry 4.0 technologies not only fosters innovation and competitive advantage, but also strengthens an organisation's ability to respond effectively to disruptions and failures (Huang et al., 2023; Jain et al., 2024).

Moreover, the profound impact of Industry 4.0 extends far beyond the realm of manufacturing, significantly affecting the overall performance of supply chains (Fatorachian & Kazemi, 2018, 2021). This transformative wave has triggered a digital metamorphosis in the supply chain domain, profoundly reshaping the business landscape (Singh et al., 2021; Witkowski, 2017). At the same time, it plays a vital role in augmenting decision making processes within organisations (Singh et al., 2021; Wiengarten & Longoni, 2015). Technologies like CPS, big data, and IoT not only enhance

system intelligence, but also have the capacity to generate innovative business models, create substantial value within various supply chain processes, and introduce dynamism across the end-to-end spectrum (Porter & Heppelmann, 2014). Leading companies are increasingly adopting these advanced technologies to digitise their operations, improve the performance of their supply chains, address operational challenges (Yang et al., 2021), and facilitate improved visibility and integration, ultimately leading to superior supply chain performance (Frank et al., 2019).

Despite the numerous advantages, the World Economic Forum reports that more than 70% of companies investing in Industry 4.0 technologies struggle to move beyond the pilot phase of adoption (Leurent and Boer 2019). The adoption of Industry 4.0 faces several challenges, of which the lack of well-defined goals stands out. These goals should elucidate the benefits and outcomes of such adoption, that is, the value brought by this transformation, and strategize a step-by-step realisation of these benefits (Demirkesen & Tezel, 2022; Leurent and Boer 2019). This study aims to address some of these significant achievements in the domains of integration and visibility. It seeks to provide insights for managers who are conducting feasibility studies for the implementation of these technologies, or who are in the process of adopting Industry 4.0. The primary objective is to explore the mechanism and impact of the adoption of Industry 4.0 technologies on enhancing integration and visibility in the supply chain, and how it can ultimately improve performance.

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Supply chain integration (SCI) involves strategic collaboration between manufacturers and their supply chain partners to optimise intra- and inter-organisational processes to deliver maximum value to customers (Flynn et al., 2010). Achieving SCI relies heavily on IT tools that facilitate real-time information sharing among supply chain partners and facilitate the development of inter-organisational strategies, processes, policies, and, most importantly, corrective and preventive actions (Perdana et al., 2019). These tools serve as a unifying platform that connects all key stakeholders, including customers, suppliers, and the internal organisation (Tiwari, 2021). Integration within SCI, i.e. a set of interactions, collaborative behaviours, or their combination, encompasses both inter- and intra-organisational collaboration (Fatorachian & Kazemi, 2021). This integration creates a dynamic flow of information throughout the entire supply chain network, which ultimately increases customer satisfaction (Erboz et al., 2022). Directly linking upstream and downstream partners through collaborative mechanisms not only reduces overall operating costs, but also contributes significantly to improving organisational performance and value.

Supply chain visibility (SCV) is the comprehensive tracking of entities within the supply chain, including their identity, location, and status, all communicated through timely event messages, including planned and actual dates/times (Francis, 2008). It relies on the efficient flow of accurate information among stakeholders throughout the supply chain process (Sharma, Kamble, et al. 2022) and is assessed based on three key dimensions: automational (access to information), informational (quality of information), and transformational (use of information) (Somapa et al., 2018). In this study, our focus is on the latter, where information from business partners is shared and leveraged to increase operational efficiency and enable the tracking, planning, and monitoring of business operations. Manufacturers need increased visibility to validate customer demands and their internal requisites (Baah et al., 2022; Chaudhuri et al., 2020). However, the often vague boundaries within supply chains result in limited visibility among various stakeholders (Carter et al., 2015). This lack of visibility into material or information flows can lead to a loss of control, thereby increasing operational risks (Chaudhuri et al., 2020). Therefore, enhancing SCV not only mitigates these risks, but also improves operational and service performance (Somapa et al., 2018).

Supply chain performance (SCP) involves the systematic measurement of the effectiveness and efficiency of supply chain operations (Sundram et al., 2016). It is a well-studied area in the literature, with performance indicators including flexibility, reliability, responsiveness, quality, and asset management (Dev et al., 2019; Najmi & Makui, 2012). According to Gunasekaran et al. (2004), SCP is an ongoing process aimed at enhancing core competitiveness and maximising efficiency and effectiveness within supply chains. In the current industrial landscape, companies are increasingly adopting advanced IT technologies associated with Industry 4.0 to optimise SCP. This approach facilitates cross-functional alignment and end-to-end connectivity, i.e. SCI, and real-time asset tracking, i.e. SCV (Asamoah et al., 2021), resulting in

improved financial and operational performance by reducing production costs and delivery times (Witkowski, 2017). Industry 4.0, therefore, seems to have a profound impact not only on the manufacturing system, but also on the overall SCP (Xie et al., 2020).

While the existing literature has made progress in exploring Industry 4.0, SCP, SCI, and SCV, there are still gaps. First, some studies discuss the impact of Industry 4.0 on SCP, but often neglect the combined influence of SCI and SCV. The few that cover all these aspects (i.e. Fatorachian and Kazemi (2021); Tiwari (2021)) focus on conceptual frameworks derived from literature reviews rather than empirical studies. Second, although the role of SCI in the relationship between Industry 4.0 and SCP has been investigated, the mediation of SCV in this relationship has not been assessed. Research has also not reached a consensus on the empirical evidence of the mediating role of SCI (Erboz et al., 2022), possibly due to evolving technologies (Rad et al., 2022), different conceptual constructs (Veile et al., 2024), and the class of countries studied (i.e. developed or developing). Third, a few studies touch on SCV in the context of Industry 4.0 and SCP, but they often fail to link SCV to the adoption of Industry 4.0 or its impact on SCP. While previous research has examined the individual effects of Industry 4.0, SCI, and SCV on SCP, there is a lack of empirical studies that examine the combined effects of SCI and SCV as mediators in Industry 4.0 environments. Addressing these gaps could provide empirical evidence to better understand the interplay between these four concepts (Agrawal et al., 2024; Hu et al., 2024; Rad et al., 2022; Veile et al., 2024). The following details these gaps and research opportunities:

- **Exploring Industry 4.0 and SCP:** Sharma et al. (2022) argue that Industry 4.0 could play a mediating role between supply chain management practices and SCP. In this regard, they examined the influence of Industry 4.0 technologies on SCP, but did not specifically investigate the role of SCI and SCV. Frederico et al. (2019) introduce a Supply Chain 4.0 framework that considers the mediating role of both SCV and SCI in the context of achieving SCP. However, their ideas remain at the conceptual framework stage and lack quantitative evaluation. Fatorachian and Kazemi (2021) discuss the impact of Industry 4.0 on SCP and consider SCI and SCV in their framework, yet the impact was not quantitatively measured.
- **Role of SCI in the relationship between Industry 4.0 and SCP:** Several studies have shed light on the role of SCI in the context of Industry 4.0 and SCP. Tiwari (2021), in a systematic review, explores the relationship between Industry 4.0 and SCI, highlighting the significant role of SCI in enhancing SCP. Di Maria et al. (2022) discuss the mediating role of SCI in relation to Industry 4.0 technologies and circular economy performance. Erboz et al. (2022) conduct a study that examines the partial mediating role of SCI between Industry 4.0 and SCP, and also assesses the direct effect of Industry 4.0 on SCP in a developing country. Rad et al. (2022) highlight SCI as a

critical success factor that promotes the impact of Industry 4.0 on SCP. Sharma, Kamble, et al. (2022) explore the direct impact of Industry 4.0 on sustainable agricultural SCP and also consider the indirect impact through SCI. Zhu et al. (2022) examine the impact of advanced IT adoption (Industry 4.0) on SCP and find a significant indirect effect mediated by SCI. However, these studies do not explicitly link SCI to SCV.

- Role of SCV in the relationship between Industry 4.0 and SCP:** A few studies have touched on the concept of SCV in the context of Industry 4.0 and SCP. Ghadge et al. (2020) conduct a study that simulates the impact of Industry 4.0 implementation on SCP, highlighting the increase in SCV as one of the consequences of Industry 4.0 adoption. Xie et al. (2020) introduce SCV as a factor that enables SCP in Industry 4.0-based smart supply chains. Qader et al. (2022) examine the impact of Industry 4.0 on SCP and explore how SCV moderates the relationship between Industry 4.0 and SCP. However, these studies do not directly link SCV to the adoption of Industry 4.0 or its impact on SCP.

This study aims to bridge these gaps by providing a comprehensive examination of the impact of Industry 4.0 adoption on SCP, with a particular focus on the mediating roles of SCI and SCV. The foundation of this research is built on a conceptual model derived from Fatorachian and Kazemi (2021), which harmonises these four critical concepts. In doing so, our research will make a substantial contribution to the existing body of knowledge by providing empirical evidence that elucidates how SCI and SCV mediate the relationship between Industry 4.0 adoption and SCP, thereby enhancing our understanding of the intricate interplay between these central elements in the context of supply chain management.

The remainder of this paper is organised as follows. In [Section 2](#), we review the materials and methods used in this study, explaining the theoretical background that underpins our research model and hypotheses, followed by a detailed description of our research methodology and data. [Section 3](#) presents the results, including the measurement model, structural model, vital important-performance map analysis, mediation analysis, and an examination of control variables. In [Section 4](#), we provide a comprehensive discussion of our findings, offering insights into the theoretical and managerial implications. Lastly, in [Section 5](#), we draw our conclusions and acknowledge the limitations while suggesting avenues for future studies.

2. Materials and methods

2.1. Theoretical background and hypothesis development

2.1.1. Resource-based view

The Resource-Based View (RBV), the primary theoretical paradigm underpinning supply chain digitalisation research (Seyedghorban et al., 2020), is a theoretical framework that

posits that a firm's sustainable competitive advantage is derived from its unique resources and capabilities. This theory, introduced by Wernerfelt (1984) and further developed by Barney (1991), suggests that resources must be valuable, rare, inimitable, and non-substitutable to provide a competitive advantage. Industry 4.0 technologies represent valuable, rare, inimitable, and non-substitutable resources that are organised to capture value and create sustainable competitive advantage (Estensoro et al., 2022). The value of Industry 4.0 technologies is evident in their ability to enhance operational efficiency, automate processes, and provide real-time data insights, as supported by studies such as that of Rosin et al. (2022) and Suchek et al. (2024), which highlight the value of these technologies in various aspects, including SCP optimisation. Furthermore, the rarity of Industry 4.0 technologies lies in their often specialised and cutting-edge nature, which makes them relatively unique within specific industries, as argued by Queiroz et al. (2022) in their research on the rarity of advanced digital technologies. Inimitability is another characteristic of Industry 4.0 technologies, as they may require significant investments, specialised knowledge, and a well-structured organisational setup to fully realise their potential, as suggested by Ghobakhloo et al. (2022). Lastly, the organisational capability to effectively leverage these technologies is supported by the study of Abiodun et al. (2023), which shows that the organisation's ability to leverage these resources is critical to achieving sustainable competitive advantage in the context of Industry 4.0.

Besides, capabilities are defined as processes unique to an organisation, whether they are formal or informal, that evolve over time through the complex allocation and use of resources and become deeply embedded in the routines of the organisation (Huo et al., 2016). The context of Industry 4.0 is firmly rooted in advanced information and manufacturing technologies that enhance the integration, visibility, and overall performance of supply chains (Qader et al., 2022; Zhu et al., 2022). SCI refers to the seamless coordination and collaboration across the supply chain, facilitated by real-time data sharing and connectivity enabled by Industry 4.0 technologies. This capability enhances flexibility, responsiveness, and efficiency in the supply chain, leading to improved SCP (Argyropoulou et al., 2024; Kamble et al., 2023). SCV involves the transparency and traceability of supply chain operations. Industry 4.0 technologies enable real-time monitoring and tracking of goods and processes, which improves decision making and reduces risk. This capability is also essential for maintaining a high level of SCP (Al-Khatib, 2023; Tan et al., 2023).

SCP represents the value or competitive advantage derived from the effective use of resources and capabilities. High SCP indicates superior operational performance, customer satisfaction, and overall business success, which are sustainable competitive advantages in the marketplace (Jum'a, 2023; Li et al., 2024). Based on the RBV framework, it is postulated that by adopting scarce resources, such as Industry 4.0 technologies, firms can further cultivate capabilities such as SCI/SCV, ultimately strengthening their competitive SCP (Qader et al., 2022). Using RBV as a theoretical

foundation, this study seeks to elucidate how a firm's resources (Industry 4.0) and capabilities (SCI and SCV) influence its overall performance (SCP). In the following sections, an in-depth exploration of how these relationships culminate in the development of each hypothesis will be provided.

2.1.2. Relationship between Industry 4.0 and SCP

On the one hand, Industry 4.0 technologies primarily aim to address the problem of resource scarcity and improve efficiency by providing strategies to optimise the use of finite resources and explore alternatives for raw materials (Fatorachian & Kazemi, 2018; Kamble & Gunasekaran, 2023; Lopes de Sousa Jabbour et al. 2018). According to Acioli et al. (2021), smart technologies in the Industry 4.0 environment are expected to deliver significant sustainable improvements in performance. This includes increased profitability, improved resource utilisation, and reduced production waste (Kamble & Gunasekaran, 2023). Pioneers in Industry 4.0 adoption, often referred to as 'lighthouse' manufacturers, are leveraging digital technologies to build more agile and customer-centric organisations. According to de Boer et al. (2022), this approach enables 'lighthouse' manufacturers to shift their focus from mere productivity to improving aspects such as sustainability, agility, speed to market, customisation, and customer satisfaction. In other words, Industry 4.0 technologies have been recognised for their contribution to industrial value creation and sustainable manufacturing, leading to improved organisational performance (Margherita & Braccini, 2023).

On the other hand, Industry 4.0 technologies themselves are considered a set of valuable resources that provide firms with the tools and data they need (Rehman et al., 2024; Seyedghorban et al., 2020), and when effectively integrated into products and business processes, they become capabilities that enable firms to perform better and gain competitive advantage (Huang et al., 2023). Numerous scholars have demonstrated how the competitive advantage resulting from Industry 4.0 technologies and practices leads to enhanced performance. For example, Jum'a (2023) shows that blockchain adoption can help firms achieve competitive advantage in the supply chain by improving productivity, lead times, customer service, relationships with supply chain members, and innovation capabilities, thereby enhancing SCP. Argyropoulou et al. (2024) illustrate how supply chains leveraging IoT and big data can create new competitive advantages by detecting trends and patterns in customer behaviour and preferences, thereby improving their performance. Wong et al. (2024) demonstrate how the use of AI in risk management provides a competitive advantage for SMEs by enabling supply chains to dynamically react to volatile environments and mitigate costly decision making processes. From a practical standpoint, Amazon's deployment of an IoT-based, AI-enabled robotic infrastructure in its warehouses has improved its competitiveness in terms of operating costs, responsiveness, and order-picking productivity, resulting in higher performance (Wang et al., 2022).

Industry 4.0 technologies, such as IoT, AI, and advanced robotics, provide firms with unique capabilities to collect,

process, and use real-time data to reduce resource consumption rates and increase productivity (Bag et al., 2023). This optimises production and value chains, allowing for improved decision making, enhanced predictive maintenance, and optimised inventory management, all of which contribute to increased operational efficiency (Ghobakhloo, 2020). In addition, the integration of digital technologies facilitates the seamless exchange of information across the supply chain, improving transparency and visibility, which enables better coordination and collaboration among supply chain partners, reducing delays and improving overall responsiveness (Cui et al., 2022). Automation and advanced analytics also streamline processes, reduce waste, and improve throughput, resulting in cost savings and faster delivery times, thereby strengthening the company's competitive position (Zamani et al., 2022). Moreover, Industry 4.0 enables greater customisation and flexibility in production processes, which allows firms within a supply chain to quickly adapt to changing market demands and offer personalised products without compromising efficiency. This adaptability is a property that increases customer satisfaction and loyalty as desired competitive advantage (Dubey et al., 2018). Lastly, continuous innovation driven by Industry 4.0 technologies enables firms to develop new products and services, thereby improving their market position (Koh et al., 2019). This innovation capability is a critical factor in maintaining long-term competitive advantage.

Inspired by such arguments, many researchers have linked Industry 4.0 and SCP, while others argue that only by enhancing capabilities such as SCI can technology truly improve performance (e.g. Delic et al. (2019); Kamble et al. (2020); Li et al. (2009)). Dalenogare et al. (2018) suggest that Industry 4.0 has the potential to enhance SCP by optimising resources and enabling agile responses to market fluctuations, thereby enhancing SCP. By adopting such technologies, firms can gain a competitive advantage through cost reduction and improved service quality. In addition, an exploratory study by Duman and Akdemir (2021) reveals a positive correlation between Industry 4.0 technologies and organisational performance metrics such as profitability, production speed, and product quality, with the potential for significant reductions in production costs. A systematic literature review by Fatorachian and Kazemi (2021) convincingly demonstrates that Industry 4.0 delivers substantial performance improvements across all supply chain processes. Similarly, through an empirical study in an emerging country, Erboz et al. (2022) highlight the direct impact of Industry 4.0 on SCP in terms of cost, delivery, and flexibility. Building on these findings, we propose the following hypothesis:

H1: *Industry 4.0 has a positive and direct effect on SCP.*

2.1.3. SCI's mediating role in industry 4.0-SCP relationship

SCI is a key capability of a firm that enables it to perform cross-functional and inter-organisational activities (Wu et al., 2006). It encompasses the firm's ability to share information and harmonise supply chain processes and decisions, not only within its own departments, but also with its suppliers

and customers. This higher order organisational capability has a significant impact on performance (Huo, 2012). In today's constantly evolving marketplace, achieving sustainable competitive advantage requires effective management of the organisation's valuable resources and the development of the necessary capabilities for their efficient configuration. This can be achieved through the internal and external integration of various activities throughout the supply chain (Argyropoulou et al., 2024). Therefore, SCI plays a pivotal role in improving performance and securing competitive advantage. This has been supported by various studies (e.g. Flynn et al. (2010); Huo (2012); Rajaguru and Matanda (2019)).

Industry 4.0 technologies emerge as valuable resources that enhance an organisation's SCI capability (Perdana et al., 2019). The adoption of Industry 4.0 technologies promotes various forms of integration—horizontal, vertical, and end-to-end (Costa et al., 2020; Reaidy et al., 2015). This integration happens in different ways. For instance, IoT and big data analytics enable real-time data sharing across the supply chain, leading to improved coordination, faster decision making, and a more responsive supply chain, thereby enhancing overall integration (Aryal et al., 2018; De Vass et al., 2018; Jiang, 2019). In addition, advanced robotics and AI automate repetitive tasks and optimise complex processes, which reduces errors and increases efficiency. This automation plays a critical role in achieving higher SCI by reducing lead times and improving coordination, resulting in a more unified and efficient supply chain network (Najat, 2024; Tiwari, 2021). Furthermore, Industry 4.0 technologies facilitate the creation of collaborative platforms where all supply chain partners can interact, share information, and collaborate in real time. These platforms foster better relationships and integration among partners (Tiwari, 2021).

Notably, the literature highlights a positive relationship between Industry 4.0 and SCI (Tiwari, 2021), with empirical studies confirming the direct impact of Industry 4.0 on SCI and its role in synchronising delivery times and improving coordination among partners. Erboz et al. (2022) argue from an RBV lens that Industry 4.0 enhances SCI by improving information sharing, managing partner relationships, and coordinating processes, while requiring new strategies and organisational inputs to sustain competitive advantage, emphasising real-time communication, and enhancing visibility and transparency for full alignment and SCI. Di Maria et al. (2022) further elaborate that Industry 4.0 technologies, primarily AI and ubiquitous systems, enhance SCI by improving automation and data flow, and changing production and coordination processes. They divide Industry 4.0 technologies into two categories: data processing and smart manufacturing, with the latter having a significant impact on SCI. Sharma, Kamble, et al. (2022) support this view, stating that Industry 4.0 technologies enhance SCI through interoperability and smart analytics. These technologies improve information sharing, reduce equipment downtime, optimise operations, and increase overall equipment effectiveness. Their empirical model, tested in the agri-food context, shows a strong positive impact of Industry 4.0 on SCI. Lastly, from an RBV perspective, Zhu et al. (2022) argue that Industry 4.0

enhances SCI when firms develop specific ICT capabilities and share them with external suppliers and customers. They differentiate SCI into internal and external integration and find a robust relationship between Industry 4.0 and both types of SCI, with a slightly higher impact on external integration. Based on these insights, we propose the following hypothesis:

H2a: *Industry 4.0 has a positive and direct effect on SCI.*

From the RBV perspective, the possession of different IT resources by firms does not automatically lead to improvements in SCP (Delic et al., 2019; Li et al., 2009). Instead, the Industry 4.0 resources that firms hold should support the development of capabilities at both the firm and supply chain levels (Argyropoulou et al., 2024; Seo et al., 2014). These capabilities can create unique and inimitable differential advantages. SCI is one such capability that can significantly enhance SCP (Frohlich & Westbrook, 2001) through several key mechanisms. SCI promotes improved coordination and collaboration among supply chain partners, resulting in synchronised operations and a reduction in redundancies and delays (Khanuja & Jain, 2019). Improved coordination enables more accurate demand forecasting and inventory management, which in turn reduces costs and improves service levels (Costantino et al., 2014). Effective SCI also ensures a seamless flow of information throughout the supply chain, providing real-time visibility into inventory levels, production schedules, and shipment status (Lee et al., 2014). This transparency facilitates rapid decision making and improves responsiveness to market changes (Munir et al., 2020). Moreover, SCI as a capability is not easily replicated by competitors due to the unique relationships and trust built between supply chain partners (Lee et al., 2016; Kumar et al., 2017). This collaborative advantage enables firms to develop customised solutions that improve overall supply chain performance.

Research has shown that SCI significantly improves SCP metrics, including cost efficiency, on-time delivery, and flexibility. Flynn et al. (2010) suggest that SCI positively impacts both operational and business performance by fostering coordination and information sharing across the supply chain. Similarly, Cao and Zhang (2011) argue that SCI enhances a firm's ability to align its resources and capabilities with market demands, leading to superior performance—at both the company and supply chain levels (Erboz et al., 2022; Huo et al., 2016). These studies highlight the importance of SCI in creating value through improved collaboration and resource utilisation. Erboz et al. (2022) further argue that SCI contributes to the development of valuable and unique firm resources, thereby enhancing firm performance, promoting sustainable competitive advantage, and positively influencing SCP through increased levels of integration and partner collaboration. Sharma, Kamble, et al. (2022) suggest that SCI enhances SCP by facilitating servitization, a key factor for competitive advantage. This is achieved through exploration and exploitation activities that lead to innovative ways to modularise and implement these approaches, thereby directly improving product-based service and customer

integration. Lastly, Di Maria et al. (2022) demonstrate that SCI enhances SCP by enabling firms to allocate valuable resources effectively, enhance internal capabilities through Industry 4.0 alignment of external resources, coordinate activities for information sharing, reduce transaction costs through efficient decision making, streamline collaboration by eliminating non-value-added activities, quickly adapt to changes in market demand, and improve product quality and delivery reliability through supplier integration. Based on this understanding, we propose the following hypothesis:

H2b: *SCI has a positive and direct effect on SCP.*

When examining the impact of Industry 4.0 on SCP, various studies have indicated that this relationship can be either direct or indirect. Li et al. (2009) find that the direct effect of IT adoption on SCP is not significant and is mediated by SCI. Delic et al. (2019) also suggest that technology alone does not have a direct effect on SCP without the mediation of SCI. In the manufacturing context, Kamble et al. (2020) show that the relationship between Industry 4.0 and SCP can be indirect and fully mediated by lean manufacturing practices. Fatorachian and Kazemi (2021) highlight the mediating effect of SCI on SCP, while Williams et al. (2013) emphasise the need to explore the effect of internal integration on operational performance dimensions. However, Erboz et al. (2022) find both a direct impact between Industry 4.0 and SCP and a partial mediating role of SCI. These mixed findings indicate a lack of consensus on the relationship between Industry 4.0 and SCP, which warrants further investigation and the formulation of additional hypotheses as follows:

H2c: *SCI mediates the relationship between Industry 4.0 and SCP.*

2.1.4. *SCV's mediating role in industry 4.0–SCP relationship*

Like SCI, SCV is a higher order capability with a significant impact on performance (Dubey et al., 2018). SCV provides a detailed view and better control of the complex movement of products, improving decision making by providing comprehensive data on supply chain operations. This enhanced visibility not only facilitates more effective supply chain planning, but also enables real-time decision making, potentially providing a sustainable competitive advantage. Studies have shown that SCV leads to improved performance metrics such as reduced lead times, lower costs, and improved service levels (e.g. Dubey et al. (2018); Somapa et al. (2018); Wamba et al. (2020)). According to RBV and the dynamic capabilities framework (Teece, 2007), visibility is a critical capability that enables firms to reconfigure resources and adapt to changing environments (Wei & Wang, 2010).

Industry 4.0 technologies are seen as valuable assets that some researchers believe will enhance SCV capabilities. For instance, Dubey et al. (2018) discover that big data and predictive analytics have a significant impact on visibility and coordination within the humanitarian supply chain. In a study on a range of advanced technologies, Zelbst et al. (2019) suggest that both IoT and blockchain technologies have a direct and positive impact on supply chain

transparency. With the aim of improving SCV, Zhao et al. (2024) introduce universal and interoperable spatiotemporal elements for cyber-physical industrial 4.0 systems. They also develop a machine learning method for accurate positioning of objects within the supply chain. There is a considerable amount of literature on SCV that discusses the use of Industry 4.0 technologies to improve traceability. However, when it comes to supply chain transparency, some studies argue that the increase is not due to the direct impact of advanced technologies. Instead, they believe that this impact is indirect and comes from the enhancement of other capabilities such as collaboration or traceability (e.g. Patil et al. (2024)).

When investigating the impact of Industry 4.0 on SCV, the majority of researchers tend to focus on a specific technology (e.g. Al-Khatib (2023); Dubey et al. (2018); Novais et al. (2019)). However, there is a noticeable lack of empirical studies investigating the impact of Industry 4.0 as a comprehensive structure that includes all relevant technologies on SCV. Recently, Jain et al. (2024) conduct a study on the mediating role of SCV between Industry 4.0 and supply chain resilience. Their survey data show that Industry 4.0 technologies increase transparency and visibility in supply chains. In another empirical study, Junaid et al. (2024) examine the impact of Industry 4.0 technologies on sustainability through SCV and circular economy practices. Their findings support the positive impact of Industry 4.0 on SCV, stating that Industry 4.0 technology enables real-time material and product tracking for SCV. In contrast, some studies report an insignificant relationship between Industry 4.0 and SCV. For example, Huang et al. (2023) explore the impact of 16 Industry 4.0 technologies and IT advancement on resilience through the mediating role of supply chain capabilities: collaboration and SCV. Following the dynamic RBV, they argue that the adoption of Industry 4.0 cannot directly affect SCV, but can do so through the mediation of IT advancement, which they view as another important IT resource with heterogeneity. This discrepancy in findings leads us to propose the following hypothesis:

H3a: *Industry 4.0 has a positive and direct effect on SCV.*

From an RBV perspective, SCV can contribute to SCP improvement in several ways. SCV enables firms to optimise the use of resources by providing accurate information on inventory levels, production schedules, and transportation. This results in reduced waste and lower operating costs (Wamba et al., 2020). With enhanced visibility, firms can identify potential disruptions early and take proactive measures to mitigate their impact. This ability is critical to maintaining continuity and performance (Brandon-Jones et al., 2014). Furthermore, SCV ensures that firms can meet delivery schedules and provide reliable service, resulting in higher customer satisfaction and loyalty. The ability to track orders in real time also improves the customer experience (Somapa et al., 2018). Lastly, SCV enables firms to respond quickly to market changes and shifts in customer demand, providing the agility needed to maintain a competitive advantage in a dynamic environment (Dubey et al., 2018).

Empirical studies in various areas of supply chain research have highlighted the positive role of SCV in enhancing SCP. Lee et al. (2014) suggest that interorganizational system visibility, an operational definition of SCV, positively affects overall SCP, particularly operational performance. Baah et al. (2022) further consider SCV as a mediator in the relationship between supply chain collaboration and performance, finding significant impacts of SCV on both environmental and financial performance. In another study by Baah et al. (2022), SCV shows significant effects on collaboration, agility, and SCP. In addition, research by Dubey et al. (2020) and Al-Khatib (2023) highlights the significant impact of SCV, particularly upstream SCV, on sustainable performance, particularly in the areas of social and environmental performance, especially when considering product complexity. Based on these findings, we propose the following hypothesis in the context of Industry 4.0:

H3b: *SCV has a positive and direct effect on SCP.*

As mentioned above, Industry 4.0 technologies such as big data analytics, IoT, and blockchain are valuable resources that appear to enhance SCV by providing real-time data and insights into supply chain operations. This enhanced visibility allows firms to optimise resource utilisation, improve decision making, and proactively manage disruptions, resulting in higher operational efficiency and performance. Studies indicate that while Industry 4.0 technologies might have a positive impact on SCV, the direct impact on SCP is not always guaranteed. Instead, SCV may act as a critical mediator, leveraging the benefits of advanced technologies to drive improvements in supply chain metrics such as reduced lead times, lower costs, and higher customer satisfaction. Thus, according to Williams et al. (2013) and Fatorachian and Kazemi (2021), the integration of Industry 4.0 technologies into supply chains may significantly enhance SCP through the mediating effect of SCV. Based on these understandings, we propose the following hypothesis:

H3c: *SCV mediates the relationship between Industry 4.0 and SCP.*

2.1.5. Relationship between SCI and SCV

SCI involves the alignment and interlinking of business processes, systems, and information flows across multiple supply chain partners. This integration allows for real-time data sharing and collaboration (Reaidy et al., 2021), resulting in improved visibility across the supply chain. Through the lens of RBV theory, when a firm integrates its supply chain, it can access and leverage the resources and capabilities of its supply chain partners. This includes real-time sharing of critical information such as inventory levels, demand forecasts, and shipment status. SCI ensures that all partners have access to accurate and timely data, improving the quality of communication and information available for visibility (Sharma, Kamble, et al. 2022). This shared visibility enables more effective and efficient decision making by allowing firms to respond more swiftly and accurately to changes in supply and demand. Moreover, SCI can lead to the development of shared systems and processes (Narasimhan et al., 2010),

further enhancing SCV. SCI aligns and synchronises processes across the supply chain, reducing discrepancies and improving the flow of information. For example, integrated IT systems can provide a single, unified view of the supply chain, making it easier to monitor and manage. Furthermore, with greater integration, firms can identify potential disruptions early, share these risks transparently with other supply chain nodes, and coordinate responses across the supply chain (Jiang et al., 2024).

The relationship between SCI and SCV has been modelled and evaluated by various researchers, with conflicting results. Recent empirical analyses by Baah et al. (2022) confirm that supply chain collaboration (i.e. SCI) have a positive and significant impact on SCV. In another empirical study by Baah et al. (2022), where information sharing and collaboration are considered separately, information sharing is found to have a positive and significant impact on both supply chain collaboration and SCV. In addition, SCV is found to have a significant effect on collaboration. In contrast, Tan et al. (2023) examine the impact of SCV on SCI. They define SCV as a combination of information exchange, business intelligence gathering, and knowledge asset status, all of which are reported to significantly affect SCI. Similarly, Hu et al. (2024) report significant influences of supply and demand visibility on both internal and external integration. These mixed findings underscore the need to further investigate the relationship between SCI and SCV. Therefore, we propose the following hypothesis:

H4: *SCI has a positive and direct effect on SCV.*

In our conceptual model, Industry 4.0 is considered as a valuable resource and is treated as an independent variable (exogenous construct), while SCP is positioned as a dependent variable (endogenous construct). SCI and SCV, considered as critical capabilities, serve as mediators in this model. In other words, in our study, Industry 4.0 (as a resource) is considered as an influencer on the development of SCI and SCV (as capabilities), and these, in turn, have an impact on SCP. This approach adheres to the basic tenets of RBV theory and the analytical capabilities of structural equation modelling (SEM) (Fan et al., 2016). Figure 1 shows the conceptual model of our study.

2.2. Research method and data

2.2.1. Research design

2.2.1.1. Instrument and data collection. The unit of analysis in our research is the adoption of Industry 4.0 technologies at the level of a strategic business unit (Weking et al., 2020). Our study consists of 157 structured interviews with managers of different firms in charge of supply chain management processes. These firms are part of 45 holding companies based in France, and are at different stages of adopting Industry 4.0 technologies in their operations. For example, Airbus SE is considered a holding company as it comprises several manufacturers and divisions, including Airbus SAS, Airbus Defence and Space, Airbus Helicopters, Airbus Corporate Jets, etc. Each division within Airbus SE operates

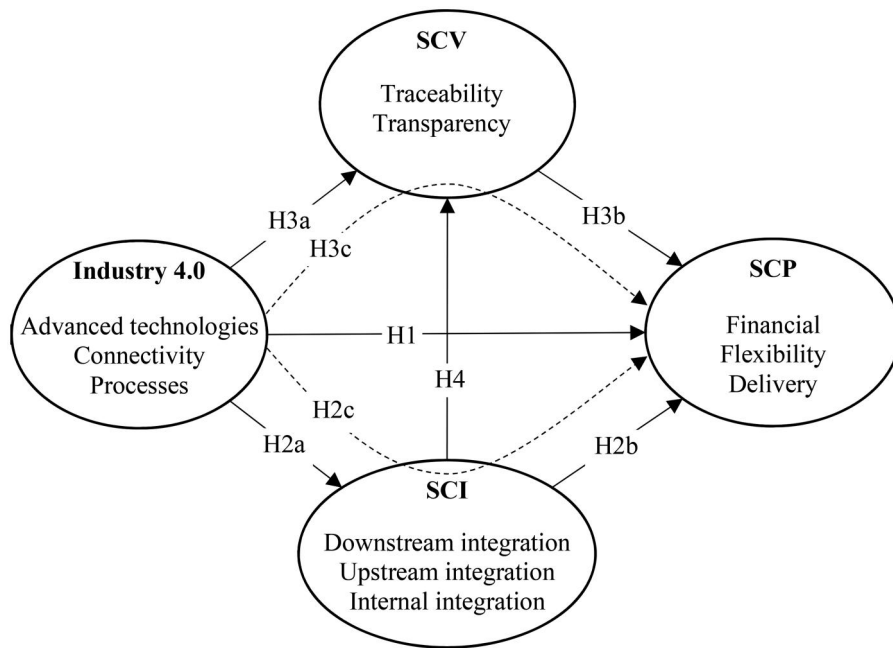


Figure 1. The research model of the study.

like a strategic business unit, with its own specific focus and operations, while contributing to the overall strategy and goals of Airbus SE. The Industry 4.0 technologies used by these Airbus subsidiaries can be both shared across the group, as well as unique to each subsidiary. For example, Airbus Helicopters may use different automation technologies than Airbus SAS, which is primarily focused on commercial aircraft.

The data collection process for this study involved emailing and/or calling 215 managers from the companies we partnered with, and 165 of them agreed to participate. However, eight interviews could not be conducted or were left unfinished due to the respondents' busy schedules, resulting in a final count of 157 completed questionnaires. There were no missing responses among these questionnaires, as we addressed any potential doubts during the interview sessions. Each interview, which was designed to elicit feedback from respondents without providing questionnaires in advance, was conducted only once with each participant. The questions revolved around their organisation's use of Industry 4.0 technologies to improve integration, visibility, and performance in their respective companies and, consequently, in their organisation's supply chain. We sought to understand how these technologies are being adopted and utilised, and the impact they are having on supply chain processes and outcomes. The decision to approach only the school's partner companies was driven by the established relationships, which facilitated smoother access to participants and ensured a higher likelihood of cooperation. Detailed information about the respondents' domains and their companies is provided in Table 1.

Based on our extensive literature review, a comprehensive questionnaire was developed for the interview sessions, covering four dimensions: Industry 4.0, SCI, SCV, and SCP. Each dimension was represented as a multidimensional construct, as outlined in Table 2. The questionnaire included numerous

items for each dimension/sub-dimension to ensure a thorough representation of the role of Industry 4.0 in supply chain management. Our purposive sampling approach focused on participants' functional roles and expertise in Industry 4.0, ensuring eligibility through our established relationships with partner companies and prior knowledge of respondents' qualifications, rather than specific company characteristics or industry sectors. Responses were measured using a Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). The structured face-to-face interviews lasted an average of 30 minutes each. To encourage candid responses and address concerns that respondents might provide expected answers, we assured participants of the anonymity and confidentiality of their responses.

During the interview sessions, we took careful steps to clarify any potential confusion that interviewees might have had, such as the difference between connectivity and integration questions. We explained that, in the context of Industry 4.0, connectivity refers to the technological infrastructure that enables seamless data flow within the company and with external partners such as suppliers and customers. On the other hand, we clarified that supply chain integration addresses the managerial practices and strategies that use this data for effective decision making and collaboration within the firm and with external partners. By distinguishing the technology-oriented nature of connectivity from the business-oriented nature of integration, we were able to help respondents understand the unique role of each construct in our research, thereby reducing the likelihood of correlated responses. This approach ensured the reliability and validity of our data collection process (Harris & Brown, 2019).

2.2.1.2. Sample size. To assess the appropriateness of our sample size of 157, a power analysis ($1-\beta$) (Cohen, 1992) was conducted. Our primary focus was on the significance of individual effects rather than the variance explained by the

Table 1. The profile of respondents.

Type of collection: structured interview		Job profile	Percentage
		Logistics	50%
Number of respondents surveyed	157	Production	18%
Sector of activity	Percentage	Planning	12%
Pharmaceutical	21%	Purchasing	8%
Automotive and aircraft	19%	Marketing and sales	6%
Electronics and IT	19%	Procurement	6%
Agribusiness	13%	Size of the firm	Percentage
Industrial machinery	8%	More than 5,000 employees	46%
Transportation	4%	Between 251 and 4,999 employees	28%
Others (chemistry, energy, etc.)	16%	Less than 250 employees	26%

overall regression equation. To assess this, a post-hoc test was performed using G*Power software (Faul et al., 2009). We used 'linear multiple regression: fixed model, single regression coefficient' method with a sample size of 157, a significance level of 0.05 and an effect size of 0.10. The results showed a significant association with a power of 0.976, exceeding the 0.80 cut-off recommended by Cohen (1992). In addition, taking into account the smallest significant effect size calculated in our model (0.043), the power remained above the cut-off at 0.827.

2.2.2. Common method bias

To reduce the common method variance, several precautions were taken during the questionnaire design and data collection process. Conducting interviews with respondents in discussion sessions allowed for a mutual understanding of the questions and encouraged them to provide honest responses, as the confidentiality of the interviews was ensured. Furthermore, we conducted statistical analysis using Harman's single factor test in SPSS software, where all constructs were subjected to principal component analysis (PCA). The results of the PCA without rotation revealed eight components that together explained 66.4% of the variance, with the first component accounting for only 26.1%. Notably, the intercorrelations shown in Table 3 did not have values greater than 0.9, with the highest intercorrelation reaching only 0.859. This analysis confirms the absence of common method bias, as neither a single dominant component emerged from the PCA nor a single overarching component accounted for most of the covariance among the measures (Podsakoff et al., 2003).

2.2.3. Measurement model selection

The partial least squares (PLS) method was chosen for this study due to its broad scope and flexibility in theory and practice, especially when the number of data is not large enough to use covariance-based methods (Sarstedt et al., 2016). PLS-based SEM, implemented using SmartPLS software, was particularly appropriate because of its ability to handle complex models with many constructs, indicators, and relationships. The measurement model, shown in Figure 1, consists entirely of reflective constructs. To ensure accurate construct specification and to avoid the errors highlighted by Petter et al. (2007), we followed the four-point guideline proposed by Jarvis et al. (2003) for determining whether a construct should be reflective or formative. To promote model

parsimony, as suggested by Johnson et al. (2011), Industry 4.0, SCI, SCV, and SCP were modelled as second-order constructs, each of which included two or three first-order constructs. The 'repeated indicators' approach described by Wold (1982) was used to estimate these reflective-reflective constructs using Mode A (Becker et al., 2012).

3. Results

3.1. Measurement model

3.1.1. Construct validity

The measurement model underwent validation to ensure the accuracy of the variables in measuring the intended concepts. Outer loadings were assessed for all reflective constructs. Most item loadings exceeded the threshold of 0.7 (Henseler et al., 2009). While a few items, such as connectivity with downstream, S&OP, and logistics processes, had loadings above 0.6 (Chin et al., 2008), they were retained because their constructs had high composite reliability (CR) and average variance extracted (AVE), with variance inflation factors (VIF) below 3.3 (Petter et al., 2007). Moreover, the goodness-of-fit (GoF) value of 0.689, calculated as $\sqrt{AVE \times R^2}$, exceeded the threshold of 0.36 (Wetzels et al., 2009). In addition, the standardised root mean square residual (SRMR) was 0.060, which is less than 0.08, indicating that the model fit was acceptable (Henseler et al., 2014).

3.1.2. Reliability

In our study, we used Cronbach's alpha values to assess reliability. All constructs showed alpha values above 0.7, confirming the reliability of our research instrument. This high consistency indicates that our survey items effectively measure the intended constructs, which increases the credibility of our findings.

3.1.3. Convergent validity

We conducted a convergent validity assessment of the measurement model using CR and AVE scores. These measures indicate the scale's relationship with related variables and other measures of the same construct. As illustrated in Table 2, our CR values exceeded the recommended threshold of 0.7, indicating a high degree of internal consistency among the indicators of each construct (Wasko & Faraj, 2005). In addition, our AVE values exceeded the 0.5 cut-off, indicating that a significant proportion of the variance in the indicators

Table 2. Validity and reliability of constructs.

Construct/Item	Item description	Loading	Alpha	CR	AVE	VIF
<i>Industry 4.0 (2nd)</i> Bibby and Dehe (2018); Erboz et al. (2022); Gold et al. (2019)			0.813	0.774	0.533	
Advanced technologies ^a (1st)		0.756	0.735	0.834	0.558	
Big data analytics and AI	Collecting, storing, and analysing large amounts of data from a variety of sources using data mining, machine learning, etc. for insightful processing	0.725				1.404
Cloud computing	Leveraging vast computing resources and storage capabilities	0.740				1.495
CPS	The use of systems with embedded software that directly record physical data using sensors and affect physical processes using actuators	0.713				1.412
IoT	The system of interconnected devices transferring data over a network autonomously	0.807				1.618
Connectivity (1st)		0.721	0.775	0.822	0.608	
Internal	Deploy and use of advanced information applications across the firm for seamless data flow	0.857				1.503
Upstream	Technological systems in place for real-time data exchange with suppliers	0.803				1.436
Downstream	Technological systems in place for real-time data exchange with customers	0.667				1.190
Processes (1st)		0.714	0.804	0.866	0.568	
S&OP	Technology support for sales and operations to efficiently balance supply and demand	0.666				1.315
Planning	Technology support for internal planning and strategizing for organisational success	0.800				1.867
Procurement	Technology support for optimal sourcing of goods and services	0.818				2.358
Production	Technology support for the effective manufacturing of products	0.840				2.286
Logistics	Technology support for ensuring smooth goods storage, transportation, etc.	0.616				1.288
<i>SCI (2nd)</i> Baah et al. (2022); Baah et al. (2022); Erboz et al. (2022)			0.700	0.829	0.620	
Internal integration (1st)		0.802	0.760	0.893	0.807	
Information sharing	Managerial practices for sharing relevant information with sales and purchasing departments	0.897				1.603
Collaboration	Managerial efforts towards decision-making synergy with sales and purchasing departments	0.899				1.603
Upstream integration (1st)		0.694	0.750	0.851	0.740	
Information sharing	Managerial practices for exchanging relevant, timely, accurate, complete information with suppliers	0.844				1.302
Collaboration	Managerial strategies for sharing benefits, costs, and risks, and jointly planning to achieve goals with suppliers	0.876				1.302
Downstream integration (1st)		0.857	0.762	0.894	0.808	
Information sharing	Managerial practices for exchanging relevant, timely, accurate, complete information with customers	0.891				1.611
Collaboration	Managerial strategies for sharing benefits, costs, and risks, and jointly planning to achieve goals with customers	0.907				1.611
<i>SCV (2nd)</i> Baah et al. (2022); Baah et al. (2022); Huang et al. (2023); Kaur et al. (2023)			0.728	0.864	0.760	
Traceability (1st)		0.909	0.862	0.820	0.695	
Performance visibility	Exchanging performance evaluation information with supply chain partners	0.843				1.180
Production visibility	Exchanging information concerning inventory and order forecasting with partners	0.824				1.180
Transparency (1st)		0.833	0.741	0.837	0.563	
Decision transparency	Involving stakeholders in customer preference and product requirement decisions	0.763				1.546
Market transparency	Informing supply chain partners on demand shifts and changes in customer preference	0.741				1.454
Risk transparency	Involving supply chain partners in the process of detecting, planning, and monitoring risks	0.785				1.705
Strategy transparency	Frequently discussing strategic issues with suppliers and customers	0.710				1.543
<i>SCP (2nd)</i> Baah et al. (2022); Baah et al. (2022); Erboz et al. (2022)			0.758	0.859	0.670	
Financial (1st)		0.811	0.723	0.843	0.642	
Production cost	Reducing total cost of manufacturing including employee, maintenance, and re-work costs	0.735				1.371
Logistics cost	Reducing total cost of logistics such as inventory, transportation, and handling costs	0.838				1.613
ROI	Increasing return on investment, i.e. the profit relative to investment cost	0.826				1.401
Flexibility (1st)		0.786	0.702	0.834	0.626	
Robustness	Ability to respond to periods of low manufacturing performance, low supplier performance, and low delivery performance	0.808				1.392
Agility	Ability to respond to demand changes such as seasonality	0.787				1.410
Adaptability	Ability to respond to new products, new markets and new competitors	0.778				1.317
Delivery (1st)		0.858	0.818	0.892	0.733	
Delivery lead time	Ability to reduce manufacturing lead time	0.892				2.237
Customer satisfaction	Low level of complaints as well as after-sales services	0.837				1.832
Delivery due date	Ability to fulfil customer orders by the promised date	0.839				1.688

Notes: $p < 0.001$ for all values.^aOther technologies with a loading less than 0.6 have been removed from the model.

can be accounted for by the latent construct (Hair et al., 2016). These results confirm the convergent validity of our measurement model, which increases the credibility of our constructs and the overall robustness of our research findings.

3.1.4. Discriminant validity

Discriminant validity was assessed to determine the uniqueness of each construct by examining the correlations between the constructs. As indicated in Table 3, the square root of the AVE for each construct (i.e. diagonal values) exceeded the corresponding correlation coefficients, confirming adequate discriminant validity (Fornell & Larcker, 1981). In addition, the heterotrait-monotrait (HTMT) ratio of correlations (Henseler et al., 2015) was used to assess discriminant validity, as shown in Table 3. According to Henseler et al. (2015), HTMT values below 0.9 indicate discriminant validity between two reflective constructs. All values were below 0.9 except for the correlation between transparency and flexibility at the attribute level, and consequently between SCV and SCP at the construct level. As suggested by Gaskin et al. (2018), this deviation is still considered acceptable because it is below 1.

3.1.5. Second-order constructs validity

The column 'loading' in Table 2 reports the weights of the first-order constructs on the corresponding second-order constructs, computed using a two-stage PLS estimation for the second-order constructs (Becker et al., 2012). These values indicate the significant connections between the second-order constructs and their first-order dimensions, confirming the validity of the constructs.

3.2. Structural model

To evaluate the structural model, we followed the guidelines of Hair et al. (2016). We evaluated R^2 , beta coefficients, and their corresponding t -values using a percentile bootstrapping procedure with 5,000 resamples. In addition, we considered the predictive relevance (Q^2) and effect size (f^2 and q^2) as supplementary measures.

3.2.1. Path coefficients

We analysed the relationships between the variables, as presented in Table 4. The adoption of Industry 4.0 in organisations had a positive and significant influence only on SCI ($\beta = 0.520$; $p < 0.001$), while it had no significant influence on SCV and SCP. Furthermore, we found strong evidence for the positive influence of SCI ($\beta = 0.237$; $p < 0.001$) and SCV ($\beta = 0.573$; $p < 0.001$) on SCP, as well as the positive effect of SCI on SCV ($\beta = 0.546$; $p < 0.001$). Thus, hypotheses H2a,b,c, H3b, and H4 were supported, while H1, H3a, and H3c were not.

3.2.2. Coefficients of determination

Table 5 reports R^2 values that indicate that Industry 4.0 explains 27.1% ($\alpha = 0.001$) of the variance in SCI. Also, Industry 4.0 and SCI together explain 39.4% ($\alpha = 0.001$) of the variance in SCV. Considering Cohen's effect size criteria (Cohen, 2013), most of the significant effects in Table 4 can be classified as large ($f^2 > 0.35$). However, the influence of SCI on SCP has a small effect size ($f^2 > 0.02$). In summary, the model suggests that the latent variables were adequately measured and showed substantial relationships, with the exception of the association between SCI and SCP.

3.2.3. Predictive relevance

Cross-validated redundancy measures using blindfolding calculation assessed predictive accuracy. Stone-Geisser's Q^2 values in Table 5 represent predictive relevance. Q^2 values greater than zero indicate the relevance of Industry 4.0 to SCI, and the ability of SCI and SCV to predict SCP. To compare predictive relevance, we employed the q^2 effect size, with values of 0.02, 0.15, and 0.35 indicating small, medium, and large relevance (Hair et al., 2016). Only the q^2 for the effect of SCI on SCP is medium. However, other q^2 values exceed 0.02, indicating good predictive relevance.

3.3. Important-performance map analysis

To identify significant antecedents and assess their performance in predicting SCP, we conducted an important-performance map analysis (IPMA) (Hair et al., 2024) at the construct level. While Tables 4 and 5 provide insight into the relative significance of constructs in explaining SCP within the structural model, the IPMA expands on these findings by considering the performance of each construct. This additional layer of information is critical to the formulation of conclusions. Consequently, conclusions are drawn based on two dimensions: importance and performance. This two-dimensional approach is particularly useful for prioritising management actions. Therefore, it is advisable to focus primarily on improving the performance of items or constructs that have high importance in explaining SCP but currently have relatively low performance (Hair et al., 2024). Figure 2 indicates three key indicators: transparency of decisions, market volatility, and risk, all of which have high importance and high performance. Increasing each of them by 1 unit leads to corresponding improvements in SCP by their respective importance values (0.153, 0.148, and 0.148). This supports hypothesis H3b by demonstrating the importance of SCV in achieving SCP.

3.4. Mediation analysis

In our model, the relationships between constructs were explored through a systematic mediation analysis, following the approach suggested by Hair et al. (2016) and Zhao et al. (2010) and using a percentile bootstrapping procedure with 5,000 subsamples. We examined how the mediator variables, SCI and SCV, together influenced the endogenous construct,

Table 3. Discriminant validity of the first-order and second-order constructs.

	Advanced IT	Connectivity	Processes	Internal integration	Upstream integration	Downstream integration	Traceability	Transparency	Financial	Flexibility	Delivery	Industry 4.0	SCI	SCV	SCP
Advanced IT	<i>0.747^a</i>														
Connectivity	0.388 ^b	<i>0.780</i>													
Processes	0.539 ^c	0.185	<i>0.754</i>												
Internal integration	0.431	0.277	0.378	<i>0.898</i>											
Upstream integration	0.369	0.241	0.489	0.415	<i>0.860</i>										
Downstream integration	0.495	0.330	0.262	0.585	0.567	<i>0.899</i>									
Traceability	0.350	0.362	0.371	0.291	0.803	0.470	<i>0.834</i>								
Transparency	0.494	0.542	0.208	0.382	0.388	0.719	0.527	<i>0.750</i>							
Financial	0.248	0.292	0.421	0.337	0.496	0.511	0.810	0.494	<i>0.801</i>						
Flexibility	0.188	0.447	0.614	0.513	0.706	0.675	0.332	0.655	0.499	<i>0.791</i>					
Delivery	0.297	0.244	0.295	0.409	0.286	0.296	0.503	0.693	0.667	0.512	<i>0.856</i>				
Industry 4.0	0.192	0.334	0.212	0.336	0.387	0.391	0.457	0.957	0.519	0.671		<i>0.730</i>			
SCI	0.102	0.204	0.207	0.252	0.433	0.470	0.731	0.564	0.670			0.520	<i>0.787</i>		
SCV	0.209	0.307	0.201	0.364	0.428	0.308	0.294	0.720				0.843	0.421	<i>0.872</i>	
SCP	0.174	0.207	0.278	0.336	0.428	0.390	0.430					0.672	0.887	0.693	<i>0.819</i>
	0.100	0.238	0.158	0.325	0.584							0.302	0.558	0.755	<i>0.911</i>
	0.150	0.321	0.198	0.413								0.452	0.755	0.911	

^aValues on the diagonal (italic) are the square roots of the AVEs, while the off-diagonals are correlations.

^bFornell-Larcker correlation between the constructs of the same order.

^cHeterotrait-monotrait (HTMT) values (underlined) for the first-order and second-order constructs.

SCP, when Industry 4.0 was the exogenous factor. The mediation effect of SCI on the relationship between Industry 4.0 and SCP was significant, with an indirect effect of $0.520 \times 0.237 = 0.123$ ($t = 2.797$) at $\alpha = 0.01$. This significance suggests an indirect-only effect (full mediation), as the direct effect of Industry 4.0 on SCP was found to be insignificant. However, regarding the mediating role of SCV in the relationship between Industry 4.0 and SCP, our data analysis did not provide evidence of such an indirect effect.

Two additional mediation effects were observed due to the significant relationship between SCI and SCV. The first is a complementary partial mediation effect, as SCV mediated the relationship between SCI and SCP. Both the direct ($\beta = 0.237$, $t = 3.190$) and indirect ($\beta = 0.546 \times 0.573 = 0.313$, $t = 5.253$) effects were significant at $\alpha = 0.001$. The product of the direct and indirect effects was positive ($0.237 \times 0.313 = 0.074 > 0$), further confirming this mediation. The second mediation effect involves the sequential mediation of Industry 4.0 on SCP through the sequence of SCI and SCV as mediators. This sequential indirect-only effect was calculated as $0.520 \times 0.546 \times 0.573 = 0.163$ ($t = 3.940$) at $\alpha = 0.001$. Considering the presence of multiple mediation effects in the model, the overall effect of Industry 4.0 on SCP can be summarised as $-0.062 + 0.123 + 0.078 + 0.163 = 0.302$ ($t = 2.976$), which is significant at $\alpha = 0.01$.

3.5. Control variables

We conducted tests to examine the impact of size, i.e. number of employees (Dubey et al., 2020), and industry as control variables, both directly on each construct and indirectly as moderators of the aforementioned effects. Notably, none of these variables had a significant effect on SCP. However, we observed an inverse relationship between size and SCV ($\beta = -0.138$, $t = 2.052$, $p < 0.05$), suggesting that as the size of firms increases, their level of visibility decreases. In addition, we found another inverse relationship between industry and SCI ($\beta = -0.177$, $t = 2.688$, $p < 0.01$). Our industry-specific coding revealed that the highest level of integration is observed in the automotive, pharmaceutical, and food industries, while the lowest level is observed in the industrial machinery and chemical industries. Despite these observations, our analysis did not reveal any significant effects in the context of the moderation of the relationship between constructs by these control variables.

4. Discussion

This study, grounded in the RBV theory, aimed to empirically investigate the relationships among four key dimensions: Industry 4.0, SCP, SCI, and SCV. Building upon the RBV framework, which suggests that IT resources and supply chain capabilities positively influence SCP, we conceptualised Industry 4.0 as a resource and SCI and SCV as capabilities that contribute to SCP. Consequently, we formulated eight hypotheses to examine both the direct and indirect effects of these resources and capabilities on SCP.

4.1. Results discussion

4.1.1. Impact of industry 4.0 adoption on supply chain capabilities

Our research is consistent with the existing literature, and also provides new insights not previously explored. We confirm a direct, positive relationship between Industry 4.0 and SCI, echoing the findings of Di Maria et al. (2022), Erboz et al. (2022), Sharma, Kamble, et al. (2022), and Zhu et al. (2022). This effect is most pronounced for upstream integration ($\beta = 0.441$, $t = 6.370$), followed by downstream integration ($\beta = 0.418$, $t = 6.208$), and internal integration ($\beta = 0.363$, $t = 4.909$), all at $\alpha = 0.001$. From the lens of RBV, the significant effect on upstream integration is due to the direct contribution of suppliers as external resources to a firm's production process (Laosirihongthong et al., 2014). Effective management of these resources through Industry 4.0 can improve efficiency, cost savings, and product quality, thus providing a competitive advantage, and therefore should be given more consideration. Downstream integration is slightly less affected, but still significant. Industry 4.0 technologies can improve customer relationships and satisfaction, leading to increased sales and market share. Internal integration is the least affected. While internal resources are important, the benefits are not as immediate or direct (Zhu et al., 2022). However, Industry 4.0 can increase coordination, communication, and efficiency within the organisation, improving overall performance.

Our results are consistent with Huang et al. (2023), who found no direct relationship between Industry 4.0 and SCV. Other prior research often focuses on specific technologies or traceability alone, rather than the diverse technologies of Industry 4.0 or the combination of traceability and transparency. Our findings suggest that the effectiveness of Industry 4.0 adoption depends on factors such as the maturity of the technology and its application in the organisation. Without robust design and continuous implementation, the effectiveness may be limited (Huang et al., 2023). Furthermore, we find that SCI mediates this relationship, making the overall effect of Industry 4.0 on SCV significant. From an RBV perspective, the insignificant direct effect of Industry 4.0 on SCV, but significant when mediated by SCI, can be understood through the distinction between resources and capabilities, and that the resources with a first-mover advantage can exert a more effective effect than those with a scale advantage (Chavez & Chen, 2022). According to Huang et al. (2023), adopting Industry 4.0 technologies alone (i.e. a scale advantage) may only help firms achieve internal capabilities, but integrating these technologies into the supply chain (i.e. a first-mover advantage) allows them to exert advantages beyond the organisation. Industry 4.0 technologies provide valuable infrastructure, but their potential to improve SCV is limited unless they are integrated and leveraged effectively. When deployed in silos, these technologies may not communicate effectively, resulting in fragmented visibility. SCI enables the seamless flow of information and heterogeneous resources, transforming the potential of Industry 4.0 technologies into enhanced SCV. This underscores the importance

Table 4. Structural estimates.

Path	Path coefficient		Hypothesis test result	f^2	q^2
	β value	t statistics			
H1: Industry 4.0→SCP	-0.062	0.921	Rejected	0.006	
H2a: Industry 4.0→SCI	0.520***	6.971	Supported	0.371*	
H3a: Industry 4.0→SCV	0.137	1.563	Rejected	0.023	
H2b: SCI→SCP	0.237**	3.190	Supported	0.061*	0.230
H3b: SCV→SCP	0.573***	9.293	Supported	0.405**	0.103
H4: SCI→SCV	0.546***	6.973	Supported	0.359*	0.051
H2c: Industry 4.0→SCI→SCP	0.123**	2.797	Supported		
H3c: Industry 4.0→SCV→SCP	0.078	1.551	Rejected		
Additional findings:					
Industry 4.0→SCI→SCV	0.284***	4.707	Significant		
SCI→SCV→SCP	0.313***	5.253	Significant		
Industry 4.0→SCI→SCV→SCP	0.163***	3.940	Significant		

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

Table 5. Coefficients of determination and predictive relevance.

Construct	R^2	t statistics	Q^2
Advanced technologies	0.602***	9.188	0.325
Connectivity	0.390***	4.632	0.226
Processes	0.596***	5.291	0.316
Internal integration	0.488***	5.071	0.381
Upstream integration	0.721***	15.456	0.525
Downstream integration	0.648***	12.224	0.513
Traceability	0.611***	8.516	0.415
Transparency	0.887***	39.789	0.488
Financial	0.646***	9.330	0.398
Flexibility	0.660***	11.943	0.403
Delivery	0.712***	13.604	0.511
SCI	0.271***	3.497	0.160
SCV	0.394***	4.710	0.282
SCP	0.510***	7.541	0.317

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

of having the right resources and the capabilities to use them effectively.

The impact of Industry 4.0 on the components of SCV is most significant for transparency ($\beta = 0.387$, $t = 4.053$), followed by traceability ($\beta = 0.321$, $t = 3.663$), both at a significance level of $\alpha = 0.001$. From the RBV standpoint, the importance of transparency can be justified by its broader and more immediate benefits, particularly in terms of information sharing through SCI and decision making. Transparency provides a comprehensive view of the supply chain and fosters better coordination and trust among partners, which are essential for improving overall performance. As a fundamental aspect of SCV, transparency is directly linked to the information-sharing capabilities enhanced by Industry 4.0 technologies. Therefore, it is not surprising that the overall impact of Industry 4.0 on transparency is the highest. This suggests that when Industry 4.0 technologies are effectively integrated through SCI, they can significantly increase the transparency of information throughout the supply chain, leading to improved decision making and performance. On the other hand, traceability, while also important, offers more specialised benefits, particularly in terms of tracking and compliance. It involves monitoring the movement of goods throughout the supply chain, a process that is more complex and may require more resources and capabilities to implement effectively. As a result, the overall impact of Industry 4.0 on traceability is lower than on transparency. This suggests that while integrated Industry 4.0 technologies can increase traceability, this increase is more challenging

and may require more advanced integration and coordination capabilities.

4.1.2. Impact of supply chain capabilities on SCP

Furthermore, our results show that there is no significant direct impact of Industry 4.0 on SCP. This finding contradicts Erboz et al. (2022), but is consistent with numerous empirical studies that emphasise that the mere implementation of technology does not guarantee an improvement in SCP (Delic et al., 2019; Li et al., 2009). Instead, firms seem to improve SCP by leveraging their capabilities, such as SCI, SCV, or their combination through digital technologies. This discrepancy in the literature may be due to differences in the Industry 4.0 components and factors considered in their models, as well as the class of countries studied. In addition, the introduction of the new SCV dimension in our model may have influenced this result, as this study supports multiple mediation relationships. The full sequential mediation, which includes the combination of SCI and SCV between Industry 4.0 and SCP, contributes a new perspective. This highlights the importance of including traceability and transparency, along with information sharing and collaboration, when exploring the relationships between supply chain concepts in an Industry 4.0 environment (Fatorachian & Kazemi, 2021).

From the lens of RBV, the implementation of I4.0 technologies (resources) without proper integration and utilisation processes (capabilities) may not directly translate into improved performance. This explains the insignificant direct impact of Industry 4.0 on SCP, as the technologies alone do not improve performance unless they are incorporated into organisational processes and practices. SCI serves as a dynamic capability, embodying a unique and difficult-to-imitate process that brings resources together to create a competitive advantage. SCI translates the potential of Industry 4.0 technologies into tangible performance improvements by forging a unified and well-coordinated supply chain network. The integration of Industry 4.0 technologies into the supply chain can strengthen coordination, information sharing, and process alignment across the supply chain, culminating in an improved SCP (Liu & Chiu, 2021). Our research also suggests that SCV can be viewed as a higher order capability that builds on the capability of SCI. The integration of Industry

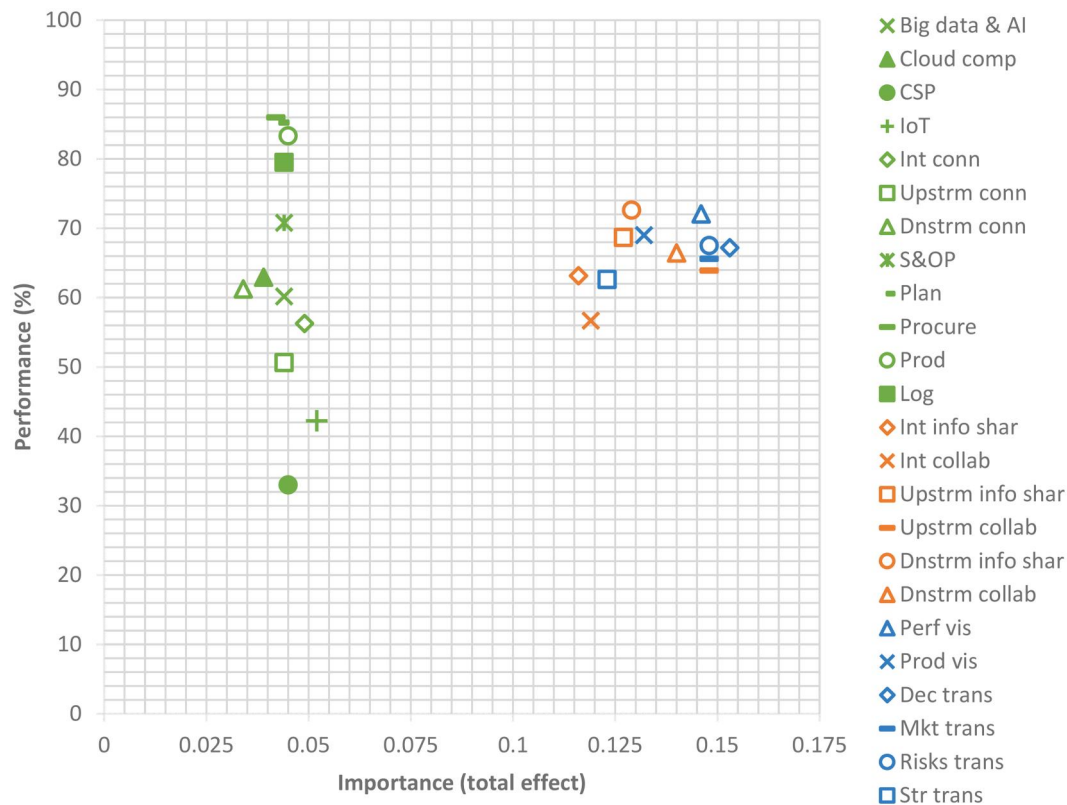


Figure 2. IPMA analysis at construct level.

4.0 technologies into the supply chain can enhance SCV by enabling real-time tracking and tracing of goods, predictive analytics for decision making, and seamless communication among supply chain partners (Xue & Li, 2023). This capability ensures that the supply chain is not only integrated, but also transparent and responsive. Enhanced visibility can lead to improved SCP by reducing uncertainty and facilitating proactive supply chain management (Zhang et al., 2023).

4.2. Theoretical implications

This study presents several theoretical implications for the literature, particularly within the RBV framework. First, our findings contribute to the understanding of resource heterogeneity (DeSarbo et al., 2007) by empirically revealing the evolution path of different resources. Industry 4.0 technologies, initially conceptualised as a scale advantage, demonstrate their potential to evolve into a first-mover advantage. The evolution from mere technology adoption to strategic integration highlights the dynamic transformation of resources in the supply chain context. This transformation underscores the importance of not only acquiring advanced technologies but also integrating them effectively to achieve competitive advantage, echoing the call by Huang et al. (2023) for a deeper understanding of resource evolution.

Second, our study contributes to RBV by demonstrating that different types of resource heterogeneity exert different influences on value creation. Specifically, Industry 4.0 technologies alone do not directly improve supply chain performance; however, when these technologies are integrated

through SCI, they significantly improve SCP. This finding aligns with the concept that superior resources, such as advanced technologies, must be coupled with capabilities, such as SCI, to realise their full value. This distinction between the scale advantage of simply adopting technologies and the first-mover advantage of effectively integrating them provides a nuanced understanding of value creation in supply chains (Chavez & Chen, 2022).

Third, our research enriches the literature by empirically examining the roles of relational and informational capabilities in supply chains. Our findings suggest that SCI, as a relational capability, and SCV, as an informational capability (Huang et al., 2023), play critical roles in mediating the effects of Industry 4.0 on SCP. SCI enhances coordination and collaboration among supply chain partners, while SCV improves transparency and traceability. This distinction highlights the complementary nature of relational and informational capabilities in achieving superior supply chain performance, and contributes to a more comprehensive understanding of how different capabilities interact to drive value creation.

Fourth, the study's findings suggest that the adoption of Industry 4.0 technologies follows a specific evolution path that enhances SCI, which in turn builds SCV as a higher order capability. This process illustrates how firms can transform technological resources into capabilities that lead to sustainable competitive advantage (D'Oria et al., 2021). By empirically demonstrating these evolution paths, our research provides insights into how firms can strategically manage their resources and capabilities to improve supply chain performance, consistent with the RBV perspective.

Lastly, our findings support the resource-capability-competitive advantage model, emphasising the need for effective integration and utilisation of resources to achieve superior performance. The study complements existing research by detailing the specific flow of relationships between Industry 4.0 technologies, SCI, SCV, and SCP. It highlights the importance of integrating traceability and transparency with information sharing and collaboration in an Industry 4.0 environment. This comprehensive approach provides a richer understanding of how digital transformation can be strategically managed to create value and sustain competitive advantage in supply chains (Leão & da Silva, 2021).

4.3. Managerial implications

Our study also provides practical implications for companies. First, this research suggests that the adoption of Industry 4.0 technologies should not be viewed in isolation, but as part of a broader strategy that integrates SCI and SCV. This perspective is critical for practitioners seeking to maximise the benefits of technology investments. By adopting a holistic approach that emphasises the development and integration of capabilities, companies can achieve more sustainable and significant improvements in supply chain performance.

Second, the study underscores the significant impact of integration across all SCP components. Managers should recognise the central role that integration plays in the supply chain and its potential to improve performance. Enhancing integration can lead to improvements in the flexibility, delivery, and financial aspects of SCP (Flynn et al., 2010). In addition, the findings suggest opportunities for managers in certain industries, such as industrial machinery and chemicals, to improve SCI. Managers in these industries might consider adopting best practices from the automotive, pharmaceutical, and food industries to identify strategies for improving their own SCI.

Third, transparency is of paramount importance, especially for stakeholders within the supply chain, including consumers. Our IPMA findings suggest that increasing transparency of decisions, markets, and risks can lead to the greatest improvement in performance. Managers need to be aware that ensuring transparency and enabling real-time information flow throughout the supply chain is fundamental to meeting consumer demands and expectations. Managers in smaller companies should recognise the potential benefits of greater supply chain visibility and explore ways to maintain and enhance that visibility. This may involve investing in technology that enhances transparency or cultivates closer relationships with suppliers and customers.

Lastly, our findings also indicate that the 'delivery' construct is more influential than 'flexibility' and 'financial' performance (see Figure 3). To improve delivery performance, firms should implement better integration and visibility within their supply chain. From a delivery perspective, the overall impact of Industry 4.0 is significant at $\alpha=0.01$ ($\beta=0.248$, $t=2.670$). Such improvements can lead to reduced delivery times, improved delivery reliability, and consistent on-time delivery. In addition, Industry 4.0 has the

potential to significantly increase supply chain flexibility ($\beta=0.238$, $t=2.667$) at $\alpha=0.01$, allowing companies to provide better customer service, reduce time-to-market, and respond rapidly to fluctuations in market demand. Furthermore, at the same level of significance, it can positively affect financial performance ($\beta=0.236$, $t=2.644$) by reducing production and logistics costs and enabling a better return on investment.

5. Conclusion

In this empirical study, we conducted a survey of 157 managers from different subsidiaries of 45 French holding companies of different sizes and industries, all involved in supply chain processes. Our research aimed to understand the relationships between Industry 4.0, integration, visibility and performance in supply chains. Surprisingly, our findings did not reveal a significant direct relationship between Industry 4.0 and supply chain performance. This suggests that the mere use of advanced technologies does not independently lead to improved performance. Instead, these technologies facilitate improved performance by strengthening capabilities such as integration with supply chain partners. In addition, our findings highlight the presence of multiple mediating roles played by integration and visibility between Industry 4.0 and performance. This deeper understanding of how Industry 4.0 affects performance underscores the importance for managers to prioritise and promote integration and visibility within their organisations. By doing so, they can maximise the benefits of implementing Industry 4.0 technologies as valuable resources.

This study has certain limitations, and there are several promising avenues for future research. The reliance on convenience and purposive sampling, focused solely on school partners, limits the generalisability of the findings, as the results may not represent organisations outside of our network. The data set is also constrained by the number of interviews conducted in France and the duration of the study. In addition, although structured interviews have better interrater agreement and less bias (Bergelson et al., 2022), respondents may have been influenced by the presence of the interviewer. Another limitation pertains to single-instrument bias. Despite having multiple interviewers to mitigate individual bias, the reliance on a single instrument in our study could potentially influence the results. To increase the generalisability of the findings and to address the aforementioned potential biases, future research should consider expanding the dataset to include data collected through a blind survey from different countries and over a longer period of time. Future research should also explore qualitative methods, such as interviews and focus groups, to provide more in-depth insights, facilitate the dissemination of knowledge, and validate the findings by capturing a broader range of perspectives and experiences.

The results of this study are based on four dimensions with a limited number of factors and items. Future research could benefit from testing additional factors and items to enrich the comprehensiveness of the model. For example,



Figure 3. Final effect of industry 4.0 on the different components of performance.

our Industry 4.0 dimension includes three factors: advanced IT, connectivity, and supply chain processes. Integrating other factors, such as employee engagement as suggested by Tortorella et al. (2021), or new dimensions and constructs, such as human-technology interaction, ethical supply chain practices, and societal impacts, could contribute to the emerging Industry 5.0 paradigm with its human-centered focus and emphasis on collaboration between humans and intelligent systems (Dacre et al., 2024). Furthermore, longitudinal studies examining the transition from Industry 4.0 to Industry 5.0 could shed light on the long-term implications of this evolution for supply chain integration, visibility, and performance in the context of sustainability and resilience.

The adoption and integration of Industry 4.0 technologies can vary significantly across firms and industries. This research may not account for varying levels of technological maturity and readiness (Schumacher et al., 2016), which can affect the effectiveness of these technologies. In addition, some firms may still be in the early stages of implementing Industry 4.0, and the long-term impacts and benefits may not yet be fully realised or captured in this study. Future research is needed to address these limitations. Furthermore, while this study highlights the mediating role of SCI and SCV, it may not fully capture the complex interplay of multiple mediators and moderators that influence the relationship among the constructs of this study. Potential moderators, such as market dynamics (Daim & Faili, 2019) and organisational culture (Tortorella et al., 2024), may influence the observed relationships but were not extensively examined by us. This is another avenue for future research. Moreover, the RBV framework, as the theoretical basis of this research, focuses primarily on internal resources and capabilities (Freiling, 2008). External factors such as competitive pressures, regulatory changes, and market conditions can also significantly influence the adoption and impact of Industry 4.0 technologies, but were not thoroughly addressed. Future studies can provide a deeper understanding of these impacts and the reasons behind them.

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Author contributions

The authors made the following significant contributions to the development and completion of this study:

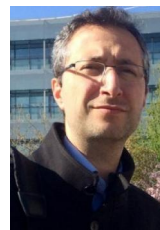
- **Conceptualisation:** Authors 1, 2, and 5
- **Methodology:** Author 2
- **Data collection:** Authors 1 and 4
- **Formal analysis:** Authors 1 and 2
- **Writing - original draft:** Authors 1, 2, and 5
- **Writing - review & editing:** Authors 1, 2, and 3
- **Supervision:** Author 3
- **Project administration:** Authors 1 and 3
- **Visualisation:** Author 2

All authors have read and approved the final manuscript and agree to take responsibility for all aspects of the work.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

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