current perspective on business operations

E-ISSN: 3125-1323

ARTICLE

Integrating Industry 4.0 Technologies for Lean an Agile Supply Chain Performance

Risa Nur Aidah [1*]

[1] Faculty of Economics and Business, Universitas Muhammadiyah Tegal, Tegal, Indonesia

* Correspondence: risanuraidah268@gmail.com

Abstract
Industry 4.0 (I4.0) technologies have opened new possibilities for improving supply chain management, but the way these tools are integrated into existing models to strengthen performance is still being explored. This study focuses on understanding how I4.0 base technologies cloud computing, the Internet of Things, and big data analytics relate to lean and agile supply chain strategies, and how they affect the operational performance of firms. These technologies are particularly important because of their ability to enhance data collection, storage, sharing, and analysis, which are key elements in modern supply chain processes. Using the Dynamic Capabilities Theory as a framework, the study applied structural equation modeling (SEM) to data collected from 256 Spanish manufacturing companies. The results show that I4.0 base technologies do not influence lean and agile supply chains in the same way. They significantly contribute to making supply chains leaner, but do not have a direct effect on agile implementation. In addition, findings highlight a connection between lean and agile strategies, where agile practices mediate the link between lean approaches and firm performance. These insights provide practical guidance for firms aiming to use I4.0 technologies to strengthen competitiveness.

Keywords: Lean Supply Chain; Agile Supply Chain; Industry 4.0 Technologies; Dynamic Capabilities

Academic Editor: Daniel Wang

Received: January 14, 2026 | Revised: January 28, 2026 | Accepted: February 9, 2026 | Published: February 15, 2026

Citation: Aidah.R.N (2026). Integrating industry 4.0 technologies for lean and agile supply chain performance. *Current Perspective on Business Operations*, 2(1), 72-91

1. Introduction

Supply chains (SCs) are increasingly challenged by global environments characterized by volatility, uncertainty, and complexity. To enhance performance, firms have traditionally relied on Lean approaches focused on eliminating non-value-adding activities and Agile approaches centered on rapidly responding to customer needs (Srinivasan et al., 2020). More recently, Industry 4.0 (I4.0) technologies have been recognized as key enablers for strengthening competitiveness in supply chains (Frederico et al., 2020; Kagermann et al., 2013). Literature highlights several I4.0 technologies, ranging from mature tools such as RFID and additive manufacturing to emerging solutions like augmented/virtual reality, the Internet of Things (IoT), and Big Data Analytics (BDA) (Ghobakhloo, 2020; Núnez-Merino et al., 2020; Oliveira-Dias et al., 2022a). Within this context, a core group of I4.0 base technologies cloud computing (CC), IoT, and BDA has been identified as critical for data-driven processes, integration, and connectivity in manufacturing systems (Frank et al., 2019; Narayanamurthy and Tortorella, 2021).

Prior research has examined their individual impact on Lean Supply Chains (LSC) and Agile Supply Chains (ASC). Raji et al. (2021a) found that BDA and IoT strongly support Lean practices, while Agile practices are more influenced by CC and cyber-physical systems. Liu et al. (2018) highlighted that CC improves IT scalability and responsiveness to market changes, whereas Reyes et al. (2021) demonstrated that BDA enables more accurate demand forecasting and reduces waste from overproduction. However, most studies remain limited to the shop-floor perspective (Tortorella et al., 2021), and little attention has been given to their broader strategic role in supply chain management.

The relationship between Lean and Agile strategies also remains debated. While some scholars view them as complementary (Narasimhan et al., 2006; Oliveira-Dias et al., 2022b; Raji et al., 2021a), others suggest they are mutually exclusive (Putnik and Putnik, 2012). Moreover, although prior works have examined their effects on operational performance (Blome et al., 2013; Garcia-Buendia et al., 2021), incorporating I4.0 base technologies as antecedents may help resolve inconsistent findings.

This study therefore aims to investigate how I4.0 base technologies influence Lean and Agile supply chain strategies and their implications for focal firms' operational performance. It specifically addresses two questions: (1) What effects do I4.0 base technologies have on Lean and Agile SC strategies and operational performance? (2) How does Lean strategy affect Agile strategy within an I4.0 environment, and what are their combined effects on performance?

Drawing on Dynamic Capabilities Theory (Teece, 2007; Yu et al., 2019), this research applies structural equation modeling (SEM) to test these relationships. From this perspective, I4.0 base technologies support the integration of SC flows, collaboration, and resource reconfiguration, thereby enabling Lean strategies to enhance customer value and Agile strategies to improve responsiveness (Enrique et al., 2022; Papanagnou et al., 2022). Since many firms struggle to achieve expected outcomes from digital investments (Attaran, 2020), empirical evidence on the alignment of technologies and strategies is critical (Moyano-Fuentes et al., 2021; Tortorella et al., 2017).

The remainder of this paper is structured as follows: Section 2 outlines the theoretical framework and hypotheses; Section 3 details the methodology; Section 4 presents findings; Section 5 discusses implications; and Section 6 concludes.

2. Literature Review and Hypothesis Development

2.1. Dynamic capabilities, Lean Supply Chain, and Agile Supply Chain

The Dynamic Capabilities View (DCV) explains how firms can reconfigure, develop, and leverage combinations of resources and capabilities to gain competitive advantage in uncertain and rapidly changing markets (Teece, 2007; Winter, 2003). This perspective extends the Resource-Based View by incorporating the dynamic nature of organizational capabilities (Teece, 2007; Winter, 2003). According to Teece (2007), dynamic capabilities consist of three main clusters: sensing, seizing, and transforming. Sensing refers to the ability to identify and assess new opportunities. Seizing involves mobilizing internal and external resources to capture value from these opportunities. Transforming relates to continuously renewing and reconfiguring resources to maintain alignment with the external environment (Teece, 2012). In operations management, the DCV has attracted growing attention (Eslami et al., 2021; Hitt et al., 2016; Rojo et al., 2018; Wamba et al., 2020), with evidence showing that dynamic capabilities can be fostered through collaboration among supply chain (SC) partners (Eslami et al., 2021). Thus, the DCV provides a useful framework for examining the links between resources, capabilities, and performance at the SC level (Hitt et al., 2016).

From this perspective, Lean Supply Chain (LSC) represents a dynamic capability whereby firms integrate, build, and reconfigure competencies to sustain competitiveness (Blome et al., 2013; Teece, 2007). LSC emphasizes eliminating non-value-adding activities while addressing individual customer needs (Iyer et al., 2019; Lamming, 1996; Srinivasan et al., 2020). Its focus lies in reducing variability and costs through more efficient resource use and stronger collaboration with suppliers and customers (Carvalho et al., 2011; Hines et al., 2004; Moyano-Fuentes et al., 2019; Qrunfleh and Tarafdar, 2013). Nevertheless, implementing Lean strategies across supply chains remains challenging (Moyano-Fuentes et al., 2021; Tortorella et al., 2017). When properly applied, however, LSC strengthens dynamic capabilities that improve quality, reduce waste, and enhance competitiveness (Iyer et al., 2019; Srinivasan et al., 2020).

Agile Supply Chain (ASC), in contrast, reflects the ability to rapidly adapt and respond to changing customer requirements (Wamba and Akter, 2019). To achieve agility, supply chains must monitor the external environment, anticipate changes, and leverage this knowledge to respond effectively to fluctuating demand (Gligor et al., 2013; Narasimhan et al., 2006; Qi et al., 2011). Deploying ASC thus builds dynamic capabilities that allow supply chains to adjust quickly and efficiently to environmental uncertainty (Eckstein et al., 2015; Wamba and Akter, 2019).

In summary, both Lean and Agile strategies can strengthen firm performance and contribute to sustainable competitive advantage. By exploiting existing resources while developing new ones, these strategies enable supply chains to build dynamic capabilities that enhance operational outcomes (Gutierrez et al., 2022; Srinivasan et al., 2020; Blome et al., 2013).

2.2. Industry 4.0 base technologies

Industry 4.0 (I4.0), also known as the Fourth Industrial Revolution, was first presented in 2011 as a paradigm for transforming the manufacturing sector through digital connectivity among machines, equipment, and human operators (Kagermann et al., 2013; Kagermann and Wahlster, 2022). The concept incorporates principles such as interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity (Hermann et al., 2015), which are enabled by a diverse set of technologies (Kagermann and Wahlster, 2022). Although scholars do not fully agree on the exact scope of I4.0 technologies (Culot et al., 2020), two main perspectives exist. One view limits I4.0 to emerging technologies like the Internet of Things (IoT) and Big Data Analytics (BDA) (Culot et al., 2020), while another broader approach considers both mature and emerging technologies collectively applied to enhance industrial performance (Frank et al., 2019; Ghobakhloo, 2020; Núñez-Merino et al., 2020; Oliveira-Dias et al., 2022a). Frank et al. (2019) classify these technologies into front-end and base groups. Front-end technologies involve advanced manufacturing, product-related innovations, horizontal integration, and human–machine interfaces, whereas base technologies specifically cloud computing

(CC), IoT, and BDA are regarded as the essential enablers that support connectivity and intelligence (Bag et al., 2021; Narayanamurthy and Tortorella, 2021). Collectively, these base technologies facilitate efficient and accurate data acquisition, storage, processing, analysis, and sharing, often with minimal human input (Fay and Kazantsev, 2018; Kamble et al., 2019). IoT enables real-time monitoring of physical assets (Manavalan and Jayakrishna, 2019), BDA processes structured and unstructured data for decision-making (Choi et al., 2018), and CC enhances accessibility and computing power for scalable analytics (Novais et al., 2019). From the dynamic capabilities perspective (Teece, 2007; Hitt et al., 2016), these base technologies represent the fundamental digital resources driving supply chain transformation and the realization of I4.0.

2.3. *I4.0 base technologies and LSC*

Recent research increasingly emphasizes the beneficial outcomes of integrating Industry 4.0 (I4.0) technologies with Lean practices (Anosike et al., 2021; Ciano et al., 2021; Kamble et al., 2019; Raji et al., 2021a). According to Ghobakhloo and Fathi (2020), the synergy between IT resources, Lean strategy, and digitalization enables firms to build a dynamic capability that is particularly valuable in the I4.0 era. Such capability strengthens an organization's ability to reconfigure IT assets and operational capacities to adapt to the uncertainties associated with digital transformation (Ghobakhloo and Fathi, 2020; Winter, 2003). Among the foundational I4.0 technologies, the Internet of Things (IoT) enhances both information and physical flows, contributing to improved decision-making, optimized routing, and shorter order cycles (Kamble et al., 2019). IoT also facilitates continuous information exchange among supply chain partners (Manavalan and Jayakrishna, 2019), reduces waste through monitoring such as temperature in perishable goods supply chains and supports preventive maintenance (Raji et al., 2021a). Big Data Analytics (BDA) further helps anticipate disruptions like port congestion or natural disasters (Choi et al., 2018), improves demand forecasting, and minimizes overproduction waste (Bag et al., 2022; Reyes et al., 2021). Cloud Computing (CC) provides scalable infrastructure that fosters collaboration, knowledge sharing, and supply chain integration (Núnez-Merino et al., 2020; Reyes et al., 2021; Maqueira et al., 2019; Novais et al., 2019, 2020), while jointly with IoT supports real-time tracking aligned with JIT principles (Reyes et al., 2021). Furthermore, e-kanban systems enabled by digitalization strengthen Lean practices by automating replenishment and reducing inefficiencies (Sanders et al., 2016; Kolberg et al., 2017). Grounded in the Dynamic Capabilities View (Teece, 2007; Winter, 2003; Gutierrez et al., 2022), these technologies represent complementary resources that collectively enhance Lean Supply Chain (LSC) strategies. Hence, we propose:

H1. *Industry 4.0 base technologies have a direct and positive influence on LSC implementation.*

2.4. *I4.0 base technologies and ASC*

From the lens of dynamic capabilities, prior research in supply chain (SC) management has emphasized that information technology resources can be combined to foster the development of dynamic capabilities within the SC (Hitt et al., 2016; Rojo et al., 2018). Earlier studies have largely investigated the effects of *Cloud Computing* (CC), *Big Data Analytics* (BDA), and the *Internet of Things* (IoT) on the adoption of *Agile Supply Chain* (ASC) in isolation.

The literature indicates that BDA enables firms to recognize customer patterns, oversee and track SC activities to identify anomalies, and anticipate possible disruptions (Wamba et al., 2020). Consequently, BDA solutions contribute to ASC goals, such as promptly detecting market changes (Dubey et al., 2019). In addition, BDA strengthens responsiveness by facilitating rapid and efficient information management across the SC and improving demand planning (Alberti-Alhtaybat et al., 2019). This capability further enhances the ability to seize market opportunities (Bag et al., 2022).

Regarding CC, several studies highlight that this technology promotes SC agility by supporting partner integration and accelerating information exchange (Novais et al., 2019; Schniederjans et al., 2016). CC also allows SCs to expand computing power more flexibly and rapidly (Liu et al., 2018), which in turn enables continuous adaptation and reconfiguration of IT resources.

In terms of IoT, the literature suggests that its applications enhance supply chain visibility by providing real-time data to improve decision-making in procurement and route optimization (Ben-daya et al., 2017). Within warehouse operations, IoT can reduce time spent on data entry and scanning tasks (Yan et al., 2014).

Furthermore, the integration of BDA, CC, and IoT creates opportunities to accelerate SC flows, generate new knowledge, and reinforce ASC adoption in volatile environments. Drawing on the dynamic capabilities framework, I4.0 core technologies support SC processes by fostering the integration of supply chain flows, building competencies through stronger collaboration, and reconfiguring both internal and external resources required for ASC strategies, which are essential to address rapid market shifts (Blome et al., 2013; Teece et al., 1997). Based on this reasoning, the following hypothesis is proposed:

H2. *I4.0 base technologies exert a direct and positive effect on ASC implementation.*

2.5. *Lean supply chain and agile supply chain*

Although earlier literature often framed Lean and Agile as two contrasting approaches (e.g., Yusuf and Adeleye, 2002), more recent studies argue for a reconciliatory perspective, emphasizing how the two can complement each other (Fadaki et al., 2020; Sharma et al., 2021). Fadaki et al. (2020) observe that many companies tend to combine Lean and Agile practices rather than strictly adhering to one model alone. Similarly, Iqbal et al. (2020) contend that the two paradigms are complementary and jointly shape organizational performance.

Empirical findings also show that successful Agile organizations frequently incorporate Lean manufacturing principles, including *Total Quality Management* (TQM) and *Just in Time* (JIT) (Ghobakhloo and Azar, 2018; Inman et al., 2011). Prior studies have further suggested that Lean principles are essential to developing Agile capabilities while optimizing the use of limited resources (Inman et al., 2011; Narasimhan et al., 2006; Vinodh et al., 2009). Because Lean Supply Chain (LSC) initiatives focus on eliminating waste and reducing process variability, they provide a foundation for greater flexibility (Abdelilah et al., 2021; Vonderembse et al., 2006).

In line with this, existing research highlights that flexibility serves as a precursor to supply chain agility (Swafford et al., 2008) and that the characteristics of SC flexibility are closely aligned with those of LSC (Maqueira et al., 2021). Therefore, drawing upon the dynamic capabilities perspective, ASC can be regarded as a higher-order capability (Blome et al., 2013; Eckstein et al., 2015), which can be effectively supported through the capabilities embedded in LSC practices. From this standpoint, a Lean SC strategy acts as an antecedent of ASC and positively contributes to achieving Agile outcomes. Based on these insights, the following hypothesis is proposed:

H3. *LSC exerts a direct and positive influence on ASC implementation in I4.0 environments.*

2.6. *Lean and agile supply chain and operational performance*

The main objective of adopting Lean and Agile supply chain (SC) strategies is to enhance SC performance. Within this research, operational performance is defined as the firm's ability to achieve efficiency through cost reduction and improved delivery outcomes (Danese et al., 2012).

The Lean Supply Chain (LSC) approach emphasizes minimizing costs and eliminating non-value-adding activities, which requires close coordination with both customers and suppliers (Garcia-Buendia et al., 2021; Qrunfleh and Tarafdar, 2014). This strategy enhances operational performance by continuously improving processes, while aligning and integrating internal and external resources along the SC. Supporting this view, Danese et al. (2012) highlight that *Just in Time* (JIT) practices help shorten overall lead times and improve delivery reliability. Similarly, Moyano-Fuentes et al. (2021) report that LSC contributes to efficiency gains by lowering costs and cycle times, as well as improving inventory turnover.

Agile Supply Chain (ASC) strategies, on the other hand, aim to strengthen operational performance by fostering cost-efficient responsiveness to market demands (Carvalho et al., 2011). Previous studies demonstrate that agility in the SC improves customer satisfaction and accelerates time-to-market, which enhances operational outcomes (DeGroote and Marx, 2013; Ngai et al., 2011; Swafford et al., 2008). Sangari and Razmi (2015) further emphasize that ASC adoption drives superior competitiveness and overall performance. In addition, ASC is seen as a source of dynamic capabilities capabilities that are difficult to trade, require long-term development, and rely on complex resource interdependencies (Blome et al., 2013; Teece et al., 1997) making it a critical enabler of firm performance (Mandal, 2018).

From the perspective of dynamic capabilities, the adoption of Lean and Agile strategies when supported by I4.0 technologies leads to the creation and utilization of diverse organizational capabilities (Gutierrez et al., 2022; Srinivasan et al., 2020). As a result, these strategies drive substantial improvements in operational performance for the focal firm. Accordingly, the following hypotheses are proposed:

H4. *LSC has a direct and positive influence on the focal firm's operational performance.*

H5. *ASC has a direct and positive influence on the focal firm's operational performance***.**

2.7. *I4.0 base technologies and operational performance*

Fundamentally, Industry 4.0 (I4.0) technologies facilitate workflow integration and automated production processes, enabling quicker decision-making, more accurate demand forecasting, and large-scale mass customization (Frank et al., 2019; Hofmann et al., 2019; Kagermann et al., 2013). As a result, the I4.0 paradigm offers numerous opportunities, such as reduced production lead times, enhanced operational efficiency, and the development of innovative business models (Hofmann and Rüsch, 2017).

In particular, prior studies have confirmed the performance benefits of these technologies. Gunasekaran et al. (2017) reported that firms leveraging Big Data Analytics (BDA) improved supply chain and organizational outcomes. Similarly, Dalenogare et al. (2018) demonstrated that Big Data and sensor-driven digital automation are strongly associated with operational improvements. Anosike et al. (2021) further provide empirical evidence showing that the primary motivation for adopting IoT in manufacturing is to enhance operational performance. Moreover, Bruque-Cámara et al. (2016) found a significant association between community-level Cloud Computing (CC) adoption and operational results, as CC strengthens interconnections among SC partners and facilitates the sharing of key information, including product design and composition.

The combined application of I4.0 base technologies also opens avenues for firms to collaborate more closely with suppliers and customers, explore new market opportunities, and identify areas for operational enhancement (Frank et al., 2019; Tortorella et al., 2020). Reported benefits include stronger integration with SC partners (Bruque-Cámara et al., 2016), higher productivity (Manavalan and Jayakrishna, 2019), lower operating costs, and improved product quality (Raut et al., 2021; Wamba et al., 2020). Based on this discussion, the following hypothesis is proposed:

H6. *I4.0 base technologies have a positive relationship with the focal firm's operational performance.*

3. Research Methods

3.1. Survey design

The present research employs a quantitative methodology to examine the proposed hypotheses, relying on data gathered through a structured questionnaire. The design and refinement of the questionnaire were conducted in three stages: first, a comprehensive literature review was undertaken to identify relevant measurement constructs; second, the preliminary version of the questionnaire was evaluated through pre-tests with five international scholars specializing in Supply Chain Management (SCM) and Information Technology; and third, pilot testing was performed with five supply chain managers to ensure the clarity, completeness, and accuracy of all items.

Because the study was carried out in a non-English-speaking setting, the questionnaire and measurement scales were translated into Spanish and subsequently back-translated into English to guarantee both linguistic precision and conceptual consistency.

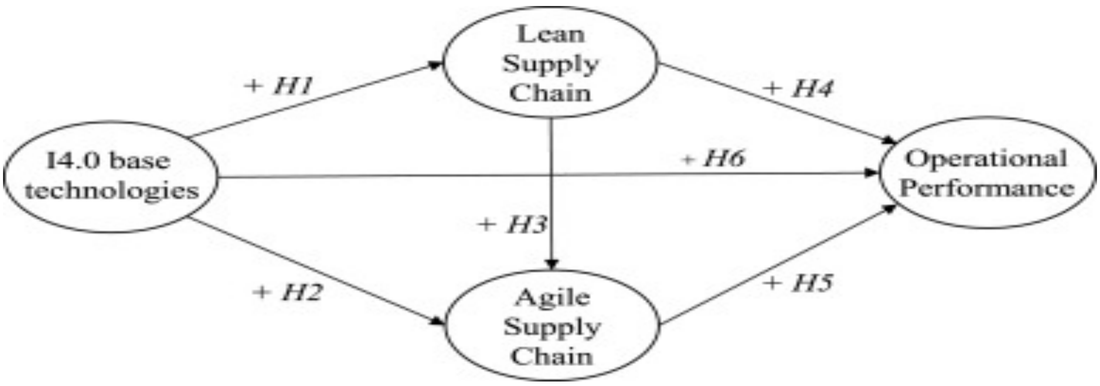

Figure 1. Theoretical model.

3.2. Variables

This study incorporates four core constructs in its theoretical model, all treated as latent variables measured indirectly. The measurement scales were drawn from validated studies and refined through pre-tests with five academic experts and pilot tests with five supply chain managers. These steps ensured that the questionnaire was well-designed to capture the targeted constructs. Detailed items are listed in Appendix A.

Lean Supply Chain (LSC) strategy. Measured as a second-order reflective construct validated in previous work (Moyano-Fuentes et al., 2019, 2021), LSC included three dimensions: (1) waste reduction tools such as VSM and Kanban (2 items); (2) operational practices like process standardization and small-lot deliveries (3 items); and (3) long-term planning covering forecasting, uncertainty management, and SC structure (3 items).

Responses were collected on a 5-point Likert scale from 1 (*strongly disagree*) to 5 (*strongly agree*).

Agile Supply Chain (ASC) strategy. ASC was operationalized as a first-order reflective construct with five items adapted from earlier studies (Gligor et al., 2013; Qi et al., 2011; Tachizawa and Gimenez, 2010). The scale captured the SC's capacity to react to customer requirements, adjust production rapidly, expand short-term capacity, and reduce delivery lead times. Measurements used a 5-point Likert scale from 1 (*strongly disagree*) to 5 (*strongly agree*). I4.0 base technologies. Based on Frank et al. (2019) and Tortorella and Fettermann (2018), this construct was measured as a first-order reflective scale including three key technologies: BDA, IoT, and CC. Adoption levels were assessed on a 5-point scale from 1 (*not implemented*) to 5 (*fully implemented*).

Operational Performance (OP). Following Danese et al. (2012) and Liu et al. (2009), OP was measured as a second-order reflective construct with two dimensions: Efficiency (3 items) and Delivery (2 items). Managers compared their firm's performance against competitors on a 5-point scale ranging from 1 (*poor/low*) to 5 (*superior*).

3.3. Sampling and data gathering

The study focused on Spanish focal manufacturing companies with at least 50 employees, positioned at intermediate levels within their supply chains. The population frame was obtained from the *Iberian Balance Sheet Analysis System* database, with firms classified based on Spain's national economic activity classification. Only manufacturing firms were retained, while extractive industries, distribution firms, and closed companies were excluded, resulting in a final list of 2,650 firms. From the focal firm perspective, managers were asked to provide both upstream and downstream supply chain views, following the approach of prior SCM research (Novais et al., 2020; van der Vaart et al., 2012).

Data were collected using the Computer-Aided Telephone Interviewing (CATI) method between January and July 2018. This technique, previously applied in SCM studies (Maqueira et al., 2019; Rojo et al., 2020), enabled random access to respondents' contact information and computerized monitoring of the process. Interviewers were specifically trained, working approximately four hours per day under the guidance of a supervisor. When questions arose beyond the scope of interviewers, a researcher was available by phone or email. The first interviews were directly supervised by the study's authors. In parallel, a web-based questionnaire was also offered for firms preferring an online response. The survey consisted of two parts: supply chain/operations/logistics directed at SCM managers, and information technology directed at IT managers. Completion required input from both respondents.

A total of 285 questionnaires were collected, yielding a 10.8% response rate, with 256 valid cases (9.7%). This response rate is consistent with prior SCM and IT studies (Queiroz et al., 2018; Tachizawa & Gimenez, 2010; Tarafdar & Qrunfleh, 2017; Wei et al., 2015), supporting the reliability of the results. Firm distribution by sector in the sample matched that of the population, ensuring representativeness. To assess potential response bias, statistical comparisons were made on firm size, operating profit, and annual sales between the sample and population, revealing no significant differences. Additionally, some non-respondents were contacted to explore reasons for refusal, but no shared patterns were found. Early and late respondent comparisons also showed no significant differences (α = 0.05).

Finally, to minimize common method bias, procedural steps were taken, including survey pre-testing and using two respondents per firm (Podsakoff et al., 2003). Harman's single-factor test showed the first factor accounted for only 21.40% of variance, confirming that common method bias was not a concern.

Table 1. Population and sample distribution by sector

Sector	Population (Number)	Population (%)	Sample (Number)	Sample (%)	Response Rate (%)
Food products and tobacco	543	20.49%	46	17.97%	8.5%
Chemicals and pharmaceutical products	422	15.92%	46	17.97%	10.9%
Manufacture of metals products	322	12.15%	42	16.41%	13.0%
Manufacture of machinery and equipment	275	10.38%	29	11.33%	10.5%
Motor vehicles	273	10.30%	21	8.20%	7.7%
Meat industry	158	5.96%	6	2.34%	3.8%
Electrical machinery and materials	141	5.32%	11	4.30%	7.8%
Manufacture of beverages	106	4.00%	6	2.34%	5.7%
Furniture industry	82	3.09%	7	2.73%	8.5%
Informatics, Electronics and Optics	81	3.06%	12	4.69%	14.8%
Manufacture of other transport material	77	2.91%	10	3.91%	13.0%
Shoes and Leather	63	2.38%	5	1.95%	7.9%
Other manufacturing industries	60	2.26%	9	3.52%	15.0%
Fabrics and Textile	47	1.77%	6	2.34%	12.8%
Total	**2650**	**100%**	**256**	**100%**	**9.7%**

Source: Author's compilation from survey data (Year).

4. Result

4.1. Measurement model

Content validity was established by relying on measurement scales widely acknowledged in prior literature (see Appendix A) and through expert review as well as pre-test procedures. An exploratory factor analysis (Table 2) was conducted to examine the unidimensionality of the constructs, producing satisfactory results for standardized factor loadings (>0.5), explained variance, and Bartlett's test ($p < 0.05$). Reliability was confirmed with Cronbach's alpha values above 0.7 (Nunnally & Bernstein, 1994).

Discriminant validity was evaluated by comparing Cronbach's α coefficients across scales (Table 2) with inter-item correlations (Table 3), following Anand and Ward (2004). In all cases, Cronbach's α values exceeded the correlation coefficients with other constructs, confirming discriminant validity.

Additionally, a confirmatory factor analysis (CFA) was performed using EQS 6.4 to verify the dimensionality of the constructs and assess convergent validity. The data exhibited multivariate non-normality, as shown by Mardia's normalized estimate, thus supporting the use of the Robust Maximum Likelihood Method. A factor model comprising 18 observed variables was developed, and the CFA results are reported in Table 4.

4.2. Structural equation model

Using the Robust Maximum Likelihood approach (Satorra, 1993) implemented in EQS 6.4, the hypotheses were tested. The analysis showed that the baseline structural model provided an acceptable fit overall (see Fig. 2). Hypotheses H1, H3, and H5 were statistically significant at $p < 0.05$, whereas H2, H4, and H6 were not (see Fig. 1). Thus, empirical support was obtained only for H1, H3, and H5.

In SEM research, exploring alternative model specifications is considered essential for validating results and understanding unexpected outcomes (Bollen & Long, 1992; Maqueira et al., 2021; Swafford et al., 2008). Accordingly, two additional models were tested to probe deeper into the nonsignificant findings of H2 and H4. Each model isolated the role of one supply chain (SC) strategy to determine how I4.0 base technologies influence performance either through Lean SC or Agile SC. By comparing these models with the baseline structure, it becomes possible to examine the distinct antecedents and consequences of LSC and ASC separately.

The first alternative (Model 1, Fig. 3) retained the paths from I4.0 base technologies to LSC (H1), from LSC to operational performance (H4), and from I4.0 base technologies directly to operational performance (H6). This model indicated a good fit (Satorra, 1993). Both H1 and H4 were validated, though H6 failed to reach significance.

The second alternative (Model 2, Fig. 3) was restricted to H2, H5, and H6. Compared to the other models, its fit was weaker (RMSEA = 0.061). The direct link between I4.0 technologies and ASC (H2) remained unsupported. A third specification assessed the direct effects of BDA, IoT, and CC on ASC. However, its fit indices were poor (RMSEA = 0.115), and none of the coefficients were significant.

Furthermore, an ANOVA test was employed to assess whether industry type and supply chain position moderated the relationship between I4.0 technologies and the two SC strategies. The analysis found no significant moderation.

Collectively, the results emphasize that I4.0 technologies influence Lean and Agile SC strategies differently. While I4.0 facilitates leaner supply chains, no evidence was found for a direct effect on agility. Both strategies are shown to affect operational performance under varying conditions, and ASC was found to mediate the effect of LSC on performance, reinforcing the interdependence of the two strategies.

Table 2. Exploratory factor analysis

Factor	Variable	Standardized Factor Loading	Cronbach's Alpha	Bartlett Test (χ^2, df, Sig.)	% Explained Variance
I4.0 base technologies	IT1	0.837	0.7	χ^2 = 133.703, df = 3, Sig. = 0.000	61.537
	IT2	0.803			
	IT3	0.708			
LSC Tooling / Operationalization	LS1	0.886	0.7	χ^2 = 270.415, df = 15, Sig. = 0.000	72.466
	LS2	0.839			
	LS3	0.821			
	LS4	0.768			
	LS5*	-			
Planning	LS6	0.684			
	LS7	0.881			
	LS8*	-			
ASC	AS1	0.629	0.8	χ^2 = 369.964, df = 10, Sig. = 0.000	54.295
	AS2	0.744			

Factor	**Variable**	**Standardized Factor Loading**	**Cronbach's Alpha**	**Bartlett Test (χ^2, df, Sig.)**	**% Explained Variance**
	AS3	0.728			
	AS4	0.792			
	AS5	0.780			
Operational Performance	EF1*	-	0.8	χ^2 = 305.026, df = 6, Sig. = 0.000	79.690
(Efficiency)	EF2	0.900			
	EF3	0.732			
Delivery	DE1	0.863			
	DE2	0.918			

Source: Author's compilation from EFA results (Year)

Table 3. Correlations between scale items

	IT1	**IT2**	**IT3**	**LS1**	**LS2**	**LS3**	**LS4**	**LS6**	**LS7**	**AS1**	**AS2**	**AS3**	**AS4**	**AS5**	**EF2**	**EF3**	**DE1**
IT1																	
IT2	0,531																
IT3	0,398	0,331															
LS1	0,202	0,192	0,198														
LS2	0,193	0,168	0,162	0,531													
LS3	0,073	0,11	0,188	0,183	0,263												
LS4	0,147	0,096	0,052	0,205	0,241	0,38											
LS6	0,188	0,118	0,144	0,129	0,231	0,301	0,343										
LS7	0,183	0,097	0,084	0,192	0,292	0,184	0,221	0,345									
AS1	0,045	-0,009	0,139	0,073	0,103	0,23	0,112	0,174	0,098								
AS2	0,12	0,081	0,01	0,013	0,085	0,125	0,08	0,24	0,056	0,407							
AS3	0,08	-0,01	0,079	-0,027	0,039	0,147	0,011	0,106	0,044	0,231	0,404						
AS4	0,083	0,026	0,075	-0,028	0,003	0,178	0,043	0,234	0,12	0,281	0,47	0,612					
AS5	0,055	-0,006	0,059	-0,002	0,092	0,249	0,2	0,259	0,16	0,495	0,454	0,408	0,494				
EF2	0,178	0,114	0,108	0,136	0,129	0,271	0,249	0,211	0,11	0,147	0,209	0,1	0,153	0,18			
EF3	-0,021	-0,119	-0,055	0,002	0,038	0,066	0,102	0,067	0,003	0,102	0,139	0,172	0,102	0,181	0,453		
DE1	0,106	-0,053	0,002	-0,068	0,042	0,025	0,154	0,073	0,112	0,166	0,204	0,194	0,164	0,253	0,36	0,484	
DE2	-0,008	-0,136	-0,024	-0,104	-0,04	-0,074	0,074	0,06	0,079	0,167	0,213	0,223	0,233	0,261	0,27	0,38	0,7

Source: Author's compilation from correlation analysis (Year).

Table 4. Confirmatory Factor Analysis

Factor	**Variable/Factor**	**Standardized Factor Loading**	**R^2**
I4.0 base technologies	IT1	0.80	0.636
	IT2	0.66	0.437
	IT3	0.51	0.256
LSC	Tooling	0.53	0.279
	Operationalization	0.82	0.669
	Planning	0.91	0.830

	LS1	0.60	0.365
	LS2	0.88	0.773
	LS3	0.61	0.367
	LS4	0.63	0.393
	LS5	0.67	0.448
	LS6	0.52	0.266
	LS7	0.52	0.270
		0.65	0.426
ASC	AS1	0.65	0.425
	AS2	0.65	0.426
	AS3	0.65	0.425
	AS4	0.73	0.537
	AS5	0.71	0.510
Operational performance	Efficency	0.83	0.690
	Delivery	0.81	0.657
	EF2	0.60	0.359
	EF3	0.76	0.573
	DE1	0.92	0.574
	DE2	0.76	0.853

Source: SmartPLS 3.0 output, processed by researcher (2025).

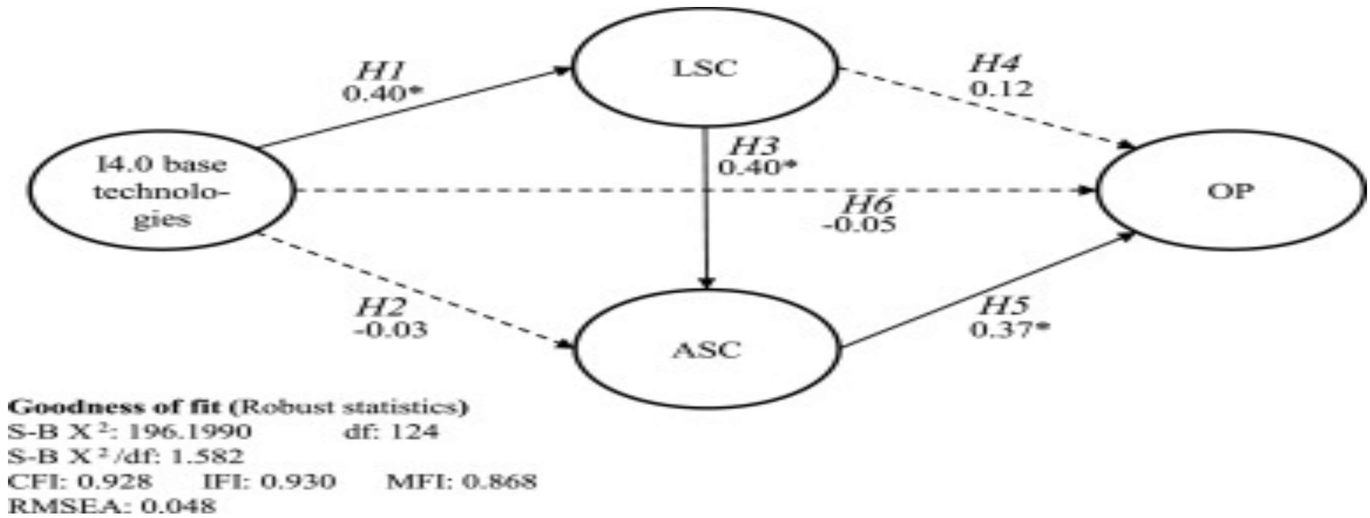

Figure 2. Baseline structural model: results.

5. Discussion

The study assessed six hypotheses to explore how I4.0 base technologies influence Lean and Agile supply chain strategies and operational performance (RQ1), and to examine the interplay between both strategies and their collective impact on performance (RQ2). Data were obtained from Spanish focal firms operating across various industries and occupying mid-level positions in supply chains, and analyzed through structural equation modeling.

For RQ1, the findings reveal that I4.0 base technologies positively and directly influence LSC (H1), whereas their direct effect on ASC is absent (H2). This implies that the adoption of BDA, IoT, and CC strengthens Lean-oriented practices in SCs, consistent with prior research (Kamble et al., 2019; Núñez-Merino et al., 2020; Raji et al., 2021a). Although emerging technologies may introduce risks of volatility and uncertainty (Oliveira-Dias et al., 2022b), the base I4.0 technologies are more established than other innovations like blockchain or AR/VR (Frank et al., 2019; Núñez-Merino et al., 2020). According to the dynamic capabilities perspective, these tools enhance the sensing capacity of LSC by detecting disruptions, improve seizing capabilities by optimizing information and material flows, and facilitate reconfiguration by enabling knowledge management and collaboration.

Contrary to expectations, H2 was not supported. The absence of a direct effect on ASC may be attributed to the fact that agility is often enabled indirectly, through factors like SC integration, collaboration, and flexibility (Oliveira-Dias et al., 2022c). Successful ASC adoption therefore depends on collaborative flows and shared information across partners (Bi et al., 2013; Liu et al., 2013; Oliveira-Dias et al., 2022a). Moreover, different technologies may exert varying impacts: while I4.0 base technologies benefit LSC, technologies such as cyber-physical systems may be more influential for ASC (Raji et al., 2021a). This highlights the need for future studies to examine how distinct technology bundles shape SC agility.

Additionally, no significant direct effect was found between I4.0 base technologies and operational performance (H6). From the lens of dynamic capabilities theory, IT resources on their own do not generate competitive advantage unless combined with complementary managerial and human assets (Novais et al., 2020; Powell & Dent-Micallef, 1997). Hence, integrating I4.0 tools with strategic and organizational resources is critical for performance improvements.

For RQ2, results indicate a positive link between LSC and ASC (H3). This suggests that agility is built upon lean foundations, as implementing LSC promotes collaboration and routine integration that enable ASC. Therefore, the effect of I4.0 base technologies on ASC may be indirect through LSC, supporting the argument that leanness precedes agility (Ghobakhloo & Azar, 2018; Iqbal et al., 2020). In addition, both strategies positively influence operational performance (H4, H5), but the direct effect of LSC disappears once ASC is accounted for in the model. This finding confirms that ASC mediates the relationship between LSC and performance, showing that agility leverages lean practices to drive operational gains.

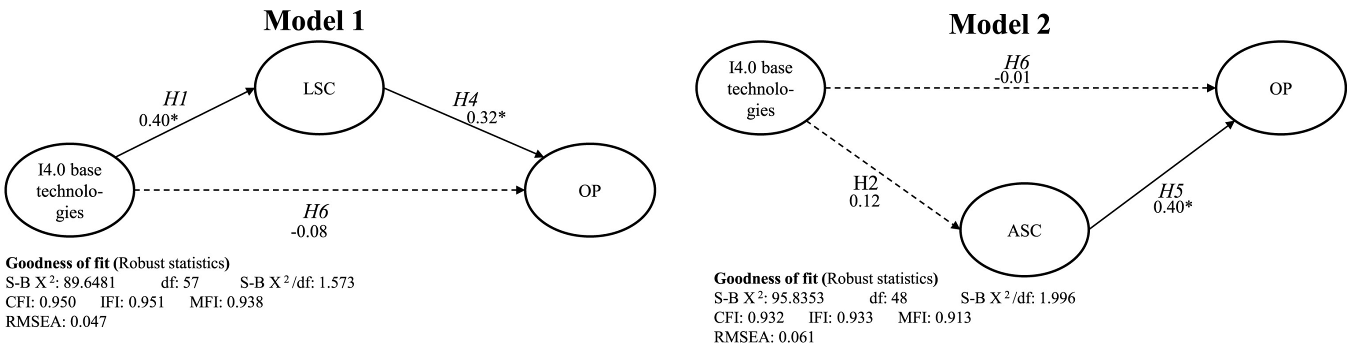

Figure 3. Alternative models: Model 1 and model 2.

6. Conclusion

This research investigated the connections between Industry 4.0 (I4.0) base technologies, Lean and Agile supply chain (SC) strategies, and operational performance. In particular, it focused on the role of three technologies cloud computing (CC), big data analytics (BDA), and the Internet of Things (IoT) in shaping Lean and Agile practices, as well as the interdependencies between these strategies and their joint effects on firm performance. The analysis was based on survey responses from 256 Spanish manufacturing firms.

From the perspective of dynamic capabilities, the findings support a direct effect model in which I4.0 technologies act as drivers of Lean SC. In turn, Lean practices positively influence Agile SC, which then enhances operational performance. Moreover, when ASC is absent, Lean SC by itself can also contribute to performance improvements (Model 1). Nevertheless, the evidence shows that ASC exerts a stronger impact on performance than LSC, even though agility tends to be reinforced by leanness.

Overall, this study sheds light on the mechanisms through which I4.0 base technologies and SC strategies interact to strengthen supply chain capabilities and drive operational performance in the context of the fourth industrial revolution.

6.1. Theoretical implications

The paper contributes to theoretical debates by filling important gaps concerning the integration of Industry 4.0 (I4.0) base technologies into supply chain (SC) strategies and by clarifying the interaction between Lean and Agile strategies under an I4.0 framework. In this respect, it advances prior scholarship (Núñez-Merino et al., 2020; Oliveira-Dias et al., 2022b; Raji et al., 2021a; Reyes et al., 2021) through empirical investigation of these underexplored connections.

Although Lean practices have previously been combined with digital technologies, much of the evidence has been limited to production-level initiatives (Tortorella et al., 2021). Less attention has been given to their adoption at the broader SC level. This study enriches the literature by demonstrating that technologies such as CC, BDA, and IoT strengthen the intelligence and interconnectivity of Lean SCs, contributing to the development of dynamic capabilities.

On the other hand, despite widespread claims about the benefits of I4.0 for Agile SC (Dubey et al., 2019; Wamba et al., 2020), our findings do not support a direct effect. Instead, they suggest that agility requires the support of complementary resources beyond base technologies. This outcome resonates with prior studies that argue for an indirect relationship between IT adoption and agility (Samdantsoodol et al., 2017; Schniederjans et al., 2016).

Moreover, this research adds theoretical value by deepening understanding of the relationship between Lean and Agile strategies and their impact on firm performance. By employing the dynamic capabilities perspective, it clarifies how these strategies serve as mechanisms for creating SC dynamic capabilities that ultimately enhance operational outcomes.

6.2. Practical implications

The findings of this research provide valuable managerial insights for supply chain (SC) practitioners regarding the role of Industry 4.0 (I4.0) base technologies in supporting Lean and Agile SC strategies, as well as their influence on operational performance.

Given that the adoption of I4.0 technologies in manufacturing remains at an early stage, this study offers guidance on how to integrate such technologies with SC strategies. The results suggest that the deployment of I4.0 base technologies alone does not directly enhance operational performance; however, it significantly contributes to the implementation of Lean SC (LSC). Consequently, the absence of a direct connection between I4.0 base technologies and performance underscores the need to view technological adoption through the lens of Lean principles. For instance, automation should target processes that create customer value, ensuring alignment with Lean practices. This study also highlights concrete ways in which LSC can be strengthened through I4.0 technologies.

Moreover, our results emphasize that firms prioritizing LSC development as an initial step are more likely to achieve Agile SC (ASC) and, eventually, improved operational performance. This demonstrates that leanness and agility should not be seen as conflicting goals but rather as complementary capabilities in an I4.0 context.

Specifically, I4.0 base technologies can reconcile tensions between LSC and ASC, such as inventory management and buffer capacity (Carvalho et al., 2011; Qrunfleh & Tarafdar, 2014), by enhancing forecasting accuracy and increasing SC visibility.

In practice, this creates a reinforcing cycle: I4.0 base technologies strengthen leanness, which facilitates agility, leading to superior performance. These improved outcomes then enable further investment in advanced technologies, thereby sustaining continuous improvement in SC capabilities.

6.3. Limitations and future studies

The findings of this study should be interpreted in light of several limitations, which also open avenues for further research. To begin with, the sample was limited to Spanish manufacturing firms, thereby reducing the external validity of the conclusions. Future studies should replicate this analysis in other geographical and economic settings, including developing economies, to broaden generalizability. Another limitation is related to the time gap since the data were collected. Although the use of more recent data would have been ideal, comparable studies investigating digital technologies have drawn on data gathered well before 2018 (e.g., Gillani et al., 2020; Di Maria et al., 2022). Future research using longitudinal datasets could offer richer insights into how digital technology adoption has progressed, particularly in the wake of the COVID-19 pandemic.

A further limitation is that only a narrow set of Industry 4.0 technologies and two supply chain strategies were examined. Subsequent studies might expand the analysis by incorporating other I4.0 technologies, testing combinations of technologies with shared features, and evaluating their role in implementing not only LSC and ASC but also hybrid, green, or resilient SC strategies. Additionally, scholars could explore which specific capabilities related to LSC and ASC are fostered by each technology and develop models that explicitly connect technological adoption, capability building, and performance outcomes.

Moreover, the significance of "small data" should not be overlooked (Bhatia et al., 2022; Wilson & Daugherty, 2020). Although cloud computing and IoT are increasingly affordable for SMEs, leveraging Big Data remains challenging due to limited resources and complexity. In such cases, smaller datasets combined with advanced analytics can still provide valuable knowledge. Lastly, further research could analyze the role of I4.0 base technologies in shaping recognized antecedents of agility such as supply chain flexibility and integration thus offering a more comprehensive picture of how agile capabilities are developed..

References

Abdelilah, B., El Korchi, A., Amine Balambo, M., 2021. Agility as a combination of lean and supply chain integration: how to achieve a better performance. Int. J. Logist. Res. Appl. 0, 1–29.

Alberti-Alhtaybat, L.V., Al-Htaybat, K., Hutaibat, K., 2019. A knowledge management and sharing business model for dealing with disruption: the case of Aramex. J. Bus. Res. 94, 400–407.

Anand, G., Ward, P.T., 2004. Fit, flexibility and performance in manufacturing: coping with dynamic environments. Prod. Oper. Manag. 13 (4), 369–385.

Anosike, A., Alafropatis, K., Garza-Reyes, J.A., Kumar, A., Luthra, S., Rocha-Lona, L., 2021. Lean manufacturing and internet of things – a synergetic or antagonist relationship? Comput. Ind. 129, 103464. Attaran, M., 2020. Digital technology enablers and their implications for supply chain management. Supply Chain Forum 21, 158–172.

Bag, S., Dhamija, P., Gupta, S., Sivarajah, U., 2021. Examining the role of procurement 4.0 towards remanufacturing operations and circular economy. Prod. Plann. Control 32 (16), 1368–1383.

Bag, S., Rahman, M.S., Srivastava, G., Chan, H.L., Bryde, D.J., 2022. The role of big data and predictive analytics in developing a resilient supply chain network in the South African mining industry against extreme weather events. Int. J. Prod. Econ. 251, 108541.

Ben-daya, M., Hassini, E., Bahroun, Z., 2017. Internet of things and supply chain management : a literature review. Int. J. Prod. Res. 7543, 1–23.

Bhatia, A.S., Kotorov, R., Chi, L., 2022. Casting plate defect detection using motif discovery with minimal model training and small data sets. J. Intell. Manuf. 0, 1–12.

Bi, R., Davison, R.M., Kam, B., Smyrnios, K.X., Davidson, R., Kam, B., Smyrnios, K.X., 2013. Developing organizational agility through IT and supply chain capability. J. Global Inf. Manag. 21 (4), 38–55.

Blome, D., Schoenherr, T., Rexhausen, C., 2013. Antecedents and enablers of supply chain agility and its effect on performance: a dynamic capabilities perspective. Int. J. Prod. Res. 51 (4), 1295–1318.

Bollen, K.A., Long, J.S., 1992. Tests for structural equation models. Socio. Methods Res. 21 (2), 123–131.

Bruque-camara, ´ S., Moyano-fuentes, J., Maqueira-Marín, J.M., 2016. Supply chain integration through community cloud : effects on operational performance. J. Purch. Supply Manag. 22 (2), 141–153.

Carvalho, H., Duarte, S., Machado, V.C., 2011. Lean, agile, resilient and green: divergencies and synergies. International Journal of Lean Six Sigma 2 (2), 151–179.

Choi, T.-M., Wallace, S.W., Wang, Y., 2018. Big data analytics in operations management. Prod. Oper. Manag. 27 (10), 1868–1883.

Ciano, M.P., Dallasega, P., Orzes, G., Rossi, T., 2021. One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study. Int. J. Prod. Res. 59 (5), 1386–1410.

Culot, G., Nassimbeni, G., Orzes, G., Sartor, M., 2020. Behind the definition of Industry 4.0: analysis and open questions. Int. J. Prod. Econ. 226, 107617.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. Int. J. Prod. Econ. 204, 383–394.

Danese, P., Romano, P., Bortolotti, T., 2012. JIT production, JIT supply and performance: investigating the moderating effects. Ind. Manag. Data Syst. 112 (3), 441–465. DeGroote, S.E., Marx, T.G., 2013. The impact of IT on supply chain agility and firm performance: an empirical investigation. Int. J. Inf. Manag. 33 (6), 909–916.

Di Maria, E., De Marchi, V., Galeazzo, A., 2022. Industry 4.0 technologies and circular economy: the mediating role of supply chain integration. Bus. Strat. Environ. 31, 619–632.

Dubey, R., Gunasekaran, A., Childe, S.J., 2019. Big data analytics capability in supply chain agility: the moderating effect of organizational flexibility. Manag. Decis. 57 (8), 2092–2112.

Eckstein, D., Goellner, M., Blome, C., Henke, M., 2015. The performance impact of supply chain agility and supply chain adaptability: the moderating effect of product complexity. Int. J. Prod. Res. 53, 3028–3046.

Enrique, D.V., Lerman, L.V., Sousa, P. R. de, Benitez, G.B., Bigares Charrua Santos, F.M., Frank, A.G., 2022. Being digital and flexible to navigate the storm: how digital transformation enhances supply chain flexibility in turbulent environments. Int. J. Prod. Econ. 250, 108668.

Eslami, M.H., Jafari, H., Achtenhagen, L., Carlb¨ ack, J., Wong, A., 2021. Financial performance and supply chain dynamic capabilities: the Moderating Role of Industry 4.0 technologies. Int. J. Prod. Res. Fadaki, M., Rahman, S., Chan, C., 2020. Leagile supply chain: design drivers and business performance implications. Int. J. Prod. Res. 58 (18), 5601–5623.

Fay, M., Kazantsev, N., 2018. When smart gets smarter: how big data analytics creates business value in smart manufacturing. In: International Conference on Information Systems 2018, ICIS 2018.

Frank, A.G., Dalenogare, L.S., Ayala, N.F., 2019. Industry 4.0 technologies: implementation patterns in manufacturing companies. Int. J. Prod. Econ. 210, 15–26. Frederico, G.F., Garza-Reyes, J.A., Anosike, A., Kumar, V., 2020. Supply Chain 4.0: concepts, maturity and research agenda. Supply Chain Manag. 25 (2), 262–282.

Garcia-Buendia, N., Moyano-Fuentes, J., Maqueira-Marín, J.M., 2021. Lean supply chain management and performance relationships: what has been done and what is left to do. CIRP J. Manufactur. Sci. Technol. 32, 405–423.

Ghobakhloo, M., 2020. Determinants of information and digital technology implementation for smart manufacturing. Int. J. Prod. Res. 58 (8), 2384–2405.

Ghobakhloo, M., Azar, A., 2018. Business excellence via advanced manufacturing technology and lean-agile manufacturing. J. Manuf. Technol. Manag. 29 (1), 2–24.

Ghobakhloo, M., Fathi, M., 2020. Corporate survival in Industry 4.0 era: the enabling role of lean-digitized manufacturing. J. Manuf. Technol. Manag. 31, 1–30.

Gillani, F., Chatha, K.A., Sadiq Jajja, M.S., Farooq, S., 2020. Implementation of digital manufacturing technologies: antecedents and consequences. Int. J. Prod. Econ. 229, 107748.

Gligor, D.M., Holcomb, M.C., Stank, T.P., 2013. A multidisciplinary approach to supply chain agility : conceptualization and scale development. J. Bus. Logist. 34 (2), 94–108.

Gunasekaran, A., Papadopoulos, T., Dubey, R., Wamba, S.F., Childe, S.J., Hazen, B., Akter, S., 2017. Big data and predictive analytics for supply chain and organizational performance. J. Bus. Res. 70, 308–317.

Gutierrez, L., Lameijer, B.A., Anand, G., Antony, J., Sunder, M.V., 2022. Beyond efficiency: the role of lean practices and cultures in developing dynamic capabilities microfoundations. Int. J. Oper. Prod. Manag. 42, 506–536.

Hermann, M., Pentek, T., Otto, B., 2015. Design Principles for Industrie 4.0 Scenarios: A Literature Review, vol. 1. Technische Universitat Dortmund, pp. 4–16. Hines, P., Holwe, M., Rich, N., 2004. Learning to evolve: a review of contemporary lean thinking. Int. J. Oper. Prod. Manag. 24 (10), 994–1011.

Hitt, M.A., Xu, K., Carnes, C.M., 2016. Resource based theory in operations management research. J. Oper. Manag. 41, 77–94. Hofmann, E., Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind. 89, 23–34.

Hofmann, E., Sternberg, H., Chen, H., Pflaum, A., Prockl, G., 2019. Supply chain management and Industry 4.0: conducting research in the digital age. Int. J. Phys. Distrib. Logist. Manag. 49 (10), 945–955.

Inman, R.A., Sale, R.S., Green, K.W., Whitten, D., 2011. Agile manufacturing: relation to JIT, operational performance and firm performance. J. Oper. Manag. 29 (4), 343–355.

Iqbal, T., Jajja, M.S.S., Bhutta, M.K., Qureshi, S.N., 2020. Lean and agile manufacturing: complementary or competing capabilities? J. Manuf. Technol. Manag. 31 (4), 749–774.

Iyer, K.N.S., Srivastava, P., Srinivasan, M., 2019. Performance implications of lean in supply chains: exploring the role of learning orientation and relational resources. Int. J. Prod. Econ. 216, 94–104.

Kagermann, H., Wahlster, W., 2022. Ten years of industrie 4.0. Sci 4 (26), 1–10.

Kagermann, H., Wahlster, W., Helbig, J., 2013. Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. https://www.din.de/blob/76902/e8cac883 f42bf28536e7e8165993f1fd/recommendations-for-implementing-industry-4-0-data. pdf.

Kamble, S., Gunasekaran, A., Dhone, N.C., 2019. Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. Int. J. Prod. Res. 58 (5), 1319–1337.

Kolberg, D., Knobloch, J., Zühlke, D., 2017. Towards a lean automation interface for workstations. Int. J. Prod. Res. 55, 2845–2856.

Lamming, R., 1996. Squaring lean supply with supply chain management. Int. J. Oper. Prod. Manag. 16 (2), 183–196.

Liu, G., McKone-Sweet, K., Shah, R., 2009. Assessing the performance impact of supply chain planning in net-enhanced organizations. Oper. Manage. Res. 2 (1), 33–43.

Liu, H., Ke, W., Wei, K.K., Hua, Z., 2013. The impact of IT capabilities on firm performance: the mediating roles of absorptive capacity and supply chain agility. Decis. Support Syst. 54 (3), 1452–1462.

Liu, S., Chan, F.T.S., Yang, J., Niu, B., 2018. Understanding the effect of cloud computing on organizational agility: an empirical examination. Int. J. Inf. Manag. 43, 98–111.

Manavalan, E., Jayakrishna, K., 2019. A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. Comput. Ind. Eng. 127, 925–953.

Mandal, S., 2018. An examination of the importance of big data analytics in supply chain agility development: a dynamic capability perspective. Manage. Res. Rev. 41, 1201–1219.

Maqueira, J.M., Moyano-Fuentes, J., Bruque, S., 2019. Drivers and consequences of an innovative technology assimilation in the supply chain: cloud computing and supply chain integration. Int. J. Prod. Res. 57 (7), 2083–2103.

Maqueira, J.M., Novais, L., Bruque-Camara, ´ S., 2021. Total eclipse on business performance and mass personalization: how supply chain flexibility eclipses lean production direct effect. Supply Chain Manag.: Int. J. 26, 256–278.

Moyano-Fuentes, J., Bruque-Camara, ´ S., Maqueira-Marín, J.M., 2019. Development and validation of a lean supply chain management measurement instrument. Prod. Plann. Control 30 (1), 20–32. Moyano-Fuentes, J., Maqueira-Marín, J.M., Martínez-Jurado, P.J., Sacrist´ an-Díaz, M., 2021. Extending lean management along the supply chain: impact on efficiency. J. Manuf. Technol. Manag. 32 (1), 63–84.

Narasimhan, R., Swink, M., Kim, S.W., 2006. Disentangling leanness and agility: an empirical investigation. J. Oper. Manag. 24 (5), 440–457.

Narayanamurthy, G., Tortorella, G., 2021. Impact of COVID-19 outbreak on employee performance – moderating role of industry 4.0 base technologies. Int. J. Prod. Econ. 234, 108075.

Ngai, E.W.T., Chau, D.C.K., Chan, T.L.A., 2011. Information technology, operational, and management competencies for supply chain agility: findings from case studies. J. Strat. Inf. Syst. 20 (3), 232–249.

Novais, L., Maqueira, J.M., Ortiz-bas, A., ´ 2019. A systematic literature review of cloud computing use in supply chain integration. Comput. Ind. Eng. 129, 296–314.

Novais, L., Maqueira-Marín, J.M., Moyano-Fuentes, J., 2020. Lean production implementation, cloud-supported logistics and supply chain integration: interrelationships and effects on business performance. Int. J. Logist. Manag. 31 (3), 629–663.

Núnez-Merino, ˜ M., Maqueira-Marín, J.M., Moyano-Fuentes, J., Martínez-Jurado, P.J., 2020. Information and digital technologies of Industry 4 . 0 and Lean supply chain management : a systematic literature review. Int. J. Prod. Res. 58 (16), 5034–5061.

Nunnally, J.C., Bernstein, I.H., 1994. The assessment of reliability. Psycometric Theory 3, 248–292.

Oliveira-Dias, D., Maqueira-Marín, J.M., Moyano-Fuentes, J., 2022a. The link between information and digital technologies of industry 4.0 and agile supply chain: mapping current research and establishing new research avenues. Comput. Ind. Eng. 167, 108000.

Oliveira-Dias, D., Maqueira-Marín, J.M., Moyano-Fuentes, J., 2022b. Lean and agile supply chain strategies: the role of Mature and Emerging Information Technologies. Int. J. Logist. Manag. 33, 221–243.

Oliveira-Dias, D., Moyano-Fuentes, J., Maqueira-Marín, J.M., 2022c. Understanding the relationships between information technology and lean and agile supply chain strategies: a systematic literature review. Ann. Oper. Res. 312, 973–1005.

Papanagnou, C., Seiler, A., Spanaki, K., Papadopoulos, T., Bourlakis, M., 2022. Datadrivendigital transformation for emergency situations: The case of the UK retail sector. Int. J. Prod. Econ. 250, 108628.

Podsakoff, P.M., MacKenzie, S.B., Lee, J.Y., Podsakoff, N.P., 2003. Common method biases in behavioral research: a critical review of the literature and recommended remedies. J. Appl. Psychol. 88, 879–903.

Powell, T.C., Dent-Micallef, A., 1997. Information technology as competitive advantage: the role of human, business, and technology resources. Strat. Manag. J. 18 (5), 375–405.

Putnik, G.D., Putnik, Z., 2012. Lean vs agile in the context of complexity management in organizations. Learn. Organ. 19, 248–266.

Qi, Y., Zhao, X., Sheu, C., 2011. The impact of competitive strategy and supply chain strategy on business performance: the role of environmental uncertainty. Decis. Sci. J. 42 (2), 371–389.

Qrunfleh, S., Tarafdar, M., 2013. Lean and agile supply chain strategies and supply chain responsiveness: the role of strategic supplier partnership and postponement. Supply Chain Manag.: Int. J. 18 (6), 571–582.

Qrunfleh, S., Tarafdar, M., 2014. Supply chain information systems strategy: impacts on supply chain performance and firm performance. Int. J. Prod. Econ. 147, 340–350.

Queiroz, M., Tallon, P.P., Sharma, R., Coltman, T., 2018. The role of IT application orchestration capability in improving agility and performance. J. Strat. Inf. Syst. 27, 4–21.

Raji, I.O., Shevtshenko, E., Rossi, T., Strozzi, F., 2021a. Industry 4.0 technologies as enablers of lean and agile supply chain strategies: an exploratory investigation. Int. J. Logist. Manag. 32 (4), 1150–1189.

Raji, I.O., Shevtshenko, E., Rossi, T., Strozzi, F., 2021b. Modelling the relationship of digital technologies with lean and agile strategies. Supply Chain Forum 22 (4), 323–346.

Raut, R.D., Mangla, S.K., Narwane, V.S., Dora, M., Liu, M., 2021. Big data analytics as a mediator in lean, agile, resilient, and green (LARG) practices effects on sustainable supply chains. Transport. Res. E Logist. Transport. Rev. 145, 102170.

Reyes, J., Mula, J., Díaz-Madronero, ˜ M., 2021. Development of a conceptual model for lean supply chain planning in industry 4.0: multidimensional analysis for operations management. Prod. Plann. Control 0 (0), 1–16.

Rojo, A.G.B., Llorens-Montes, F.J., Perez-Arostegui, M.N., Stevenson, M., 2020. Ambidextrous supply chain strategy and supply chain flexibility: the contingent effect of ISO 9001. Ind. Manag. Data Syst. 120, 1691–1714.

Rojo, A., Stevenson, M., Llor´ens Montes, F.J., Perez-Arostegui, M.N., 2018. Supply chain flexibility in dynamic environments: the enabling role of operational absorptive capacity and organisational learning. Int. J. Oper. Prod. Manag. 38, 636–666.

Samdantsoodol, A., Cang, S., Yu, H., Eardley, A., Buyantsogt, A., 2017. Predicting the relationships between virtual enterprises and agility in supply chains. Expert Syst. Appl. 84, 58–73.

Sanders, A., Elangeswaran, C., Wulfsberg, J., 2016. Industry 4.0 implies lean manufacturing: research activities in industry 4.0 function as enablers for lean manufacturing. J. Ind. Eng. Manag. 9, 811–833.

Sangari, M.S., Razmi, J., 2015. Business intelligence competence, agile capabilities, and agile performance in supply chain an empirical study. Int. J. Logist. Manag. 26 (2), 356–380.

Satorra, A., 1993. Multi-sample analysis of moment-structures: asymptotic validity of inferences based on second-order moments. In: Haagen, M., Bartholomeusz, K., Deistler, A. (Eds.), Statistical Modelling and Latent Variables. Elsevier, North Holland, Amsterdam, pp. 283–298.

Schniederjans, D.G., Ozpolat, K., Chen, Y., 2016. Humanitarian supply chain use of cloud computing. Supply Chain Manag.: Int. J. 21 (5), 569–588.

Sharma, V., Raut, R.D., Mangla, S.K., Narkhede, B.E., Luthra, S., Gokhale, R., 2021. A systematic literature review to integrate lean, agile, resilient, green and sustainable paradigms in the supply chain management. Bus. Strat. Environ. 30 (2), 1191–1212.

Srinivasan, M., Srivastava, P., Iyer, K.N.S., 2020. Response strategy to environment context factors using a lean and agile approach: implications for firm performance. Eur. Manag. J. 38 (6), 900–913.

Swafford, P.M., Ghosh, S., Murthy, N., 2008. Achieving supply chain agility through IT integration and flexibility. Int. J. Prod. Econ. 116, 288–297.

Tachizawa, E.M., Gimenez, C., 2010. Supply flexibility strategies in Spanish firms: results from a survey. Int. J. Prod. Econ. 124 (1), 214–224.

Tarafdar, M., Qrunfleh, S., 2017. Agile supply chain strategy and supply chain performance: complementary roles of supply chain practices and information systems capability for agility. Int. J. Prod. Res. 55, 925–938.

Teece, D.J., 2012. Dynamic capabilities: routines versus entrepreneurial action. J. Manag. Stud. 49, 1395–1401.

Teece, D.J., 2007. Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. Strat. Manag. J. 28 (13), 1319–1350.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strategic Mangement Journal 18, 509–533.

Tortorella, G.L., Cawley Vergara, A., Mac Garza-Reyes, J.A., Sawhney, R., 2020. Organizational learning paths based upon industry 4.0 adoption: an empirical study with Brazilian manufacturers. Int. J. Prod. Econ. 219, 284–294.

Tortorella, G.L., Fettermann, D., 2018. Implementation of industry 4.0 and lean production in brazilian manufacturing companies. Int. J. Prod. Res. 56 (8), 2975–2987.

Tortorella, G.L., Miorando, R., Marodin, G., 2017. Lean supply chain management: empirical research on practices, contexts and performance. Int. J. Prod. Econ. 193, 98–112.

Tortorella, G.L., Saurin, T.A., Filho, M.G., Samson, D., Kumar, M., 2021. Bundles of Lean Automation practices and principles and their impact on operational performance. Int. J. Prod. Econ. 235, 108106. van der Vaart, T., van Donk, D.P., Gimenez, C., Sierra, V., 2012. Modelling the integration-performance relationship: collaborative practices, enablers and contextual factors. Int. J. Oper. Prod. Manag. 32, 1043–1074.

Vinodh, S., Sundararaj, G., Devadasan, S.R., 2009. Total agile design system model via literature exploration. Ind. Manag. Data Syst. 109 (4), 570–588.

Vonderembse, M.A., Uppal, M., Huang, S.H., Dismukes, J.P., 2006. Designing supply chains: towards theory development. Int. J. Prod. Econ. 100, 223–238.

Wamba, S.F., Akter, S., 2019. Understanding supply chain analytics capabilities and agility for data-rich environments. Int. J. Oper. Prod. Manag. 39 (6), 887–912.

Wamba, S.F., Dubey, R., Gunasekaran, A., Akter, S., 2020. The performance effects of big data analytics and supply chain ambidexterity: the moderating effect of environmental dynamism. Int. J. Prod. Econ. 222, 107498.

Wei, J., Lowry, P.B., Seedorf, S., 2015. The assimilation of RFID technology by Chinese companies: a technology diffusion perspective. Inf. Manag. 52, 628–642.

Wilson, H., Daugherty, P., 2020. Small data can play A big role in ai. Harv. Bus. Rev. https://hbr.org/2020/02/small-data-can-play-a-big-role-in-ai.

Winter, S.G., 2003. Understanding dynamic capabilities. Strat. Manag. J. 24, 991–995.

Yan, J., Xin, S., Liu, Q., Xu, W., Yang, L., Fan, L., et al., 2014. Intelligent supply chain integration and management based on cloud of things. Int. J. Distributed Sens. Netw. 2014, 1–15.

Yu, W., Jacobs, M.A., Chavez, R., Yang, J., 2019. Dynamism, disruption orientation, andresilience in the supply chain and the impacts on financial performance: A dynamiccapabilities perspective. Int. J. Prod. Econ. 218, 352–362.

Yusuf, Y.Y., Adeleye, E.O., 2002. A comparative study of lean and agile manufacturing with a related survey of current practices in the UK. Int. J. Prod. Res. 40 (17), 4545–4562.