

Supply Chain 4.0 Adaptability and Lean Supply Chain Management: Connections and Impact on Firms' Operational Performance

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ABSTRACT

This study aims to (1) develop an estimation tool for assessing Supply Chain 4.0 adaptability through a hypothetical ambidextrous perspective to support the advancement of Industry 4.0, and (2) empirically examine how ambidextrous Supply Chain 4.0 capabilities and supply chain management practices contribute to enhancing firms' operational performance. The analysis is based on data collected from a pilot study involving 197 mid-tier automotive firms within the supply chain. Additional condition modeling was conducted to test the three proposed hypotheses. Drawing on the asset coordination theory and the social resource-based view, the study empirically identifies the full mediating role of supply chain management in the relationship between Supply Chain 4.0 adaptability and operational performance. This research is among the first to conceptualize the transition toward Supply Chain 4.0 within a theoretical framework while also developing a corresponding measurement scale. The findings highlight the critical role of inter-organizational ambidextrous capabilities in driving successful implementation of Industry 4.0.

KEYWORDS

Supply chain 4.0
Operational performance
Industry 4.0 technologies
Lean supply chain

INTRODUCTION

In an era marked by rapid technological advancements and heightened global competition, supply chains are increasingly compelled to adopt Industry 4.0 technologies to maintain a sustainable strategic advantage (Frederico, 2021; Bravo et al., 2023). Digital transformation demands the seamless integration of legacy information systems with advanced web-based technologies, thereby enhancing operational efficiency and agility (Alzoubi & Yanamandra, 2020; Müller et al., 2020). However, despite the transformative potential of Industry 4.0, its implementation across organizations remains uneven, and its full implications for Supply Chain Management (SCM) are not yet fully understood (Fuentes et al., 2020a; Raji et al., 2021). Organizations exhibit varying degrees of adoption, reflecting diverse levels of technological integration and strategic engagement within their supply chain operations (Isthaque et al., 2020). As such, successful digital transformation hinges on an organization's ability to balance the pursuit of emerging innovations with the refinement of existing capabilities. In this context, inter-organizational flexibility has

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emerged as a critical theoretical construct for advancing both Industry 4.0 adoption and SCM practices, emphasizing the need for adaptable and responsive supply chain strategies (Rondero et al., 2019; Ellitian, 2020).

Given the relatively recent emergence of Industry 4.0 technologies (Dias et al., 2022), their successful adoption demands a strategic blend of experimentation, innovation, and calculated risk-taking—central themes in current scholarly discourse (Liboni et al., 2019; Mate, 2022). Strategic investments in cutting-edge technologies are pivotal to support this exploratory process (Rintala et al., 2022). At the same time, organizations must simultaneously leverage and optimize existing supply chain resources and Industry 4.0 technologies to drive operational efficiency. Recent studies highlight the importance of investigating SCM 4.0 flexibility as a mechanism to reconcile the dual demands of exploration and exploitation (Shukor et al., 2021). In response to this identified research gap, the present study proposes a novel framework for evaluating SC4.0 flexibility, with a particular focus on the dynamic interaction between the optimization of current technological assets and the continuous pursuit of innovation (Lerman et al., 2022).

The mere acquisition of new technologies is insufficient to yield significant performance improvements. Successful adoption depends on fostering a culture of continuous improvement, supported by effective resource management, organizational capabilities, and strategic leadership (Wei et al., 2022). In this context, Lean Supply Chain Management (LSCM) serves as a complementary approach, enabling the integration of Industry 4.0 technologies through the application of lean principles that promote operational efficiency and effectiveness (Vega et al., 2023; McDermott et al., 2024; Nikneshan et al., 2023). Achieving competitive advantage in contemporary supply chains increasingly relies on the synergistic alignment of LSCM, information technology (IT) utilization, and comprehensive management systems.

Building on prior research, this study investigates the interaction between Industry 4.0 technologies and complementary management strategies (Tortorella et al., 2020), with a particular focus on the role of LSCM in balancing the exploration and exploitation of SC4.0 resources. Specifically, it examines whether SC4.0 flexibility—defined as the degree of adaptability in supply chain technology investments—moderates the relationship between resource orchestration and operational performance. This analytical approach is grounded in the principles of Resource Orchestration Theory (ROT) (Hamdan et al., 2020; Alkhatib & Momani, 2023; Vega et al., 2023). Furthermore, by integrating a human resource-based perspective (Kodua, 2019a), the study provides a deeper understanding of how LSCM enhances supply chain capabilities and drives improved performance outcomes. The findings offer meaningful contributions to both academic research and managerial practice by presenting a comprehensive framework for assessing SC4.0 adaptability and its impact on operational performance. By addressing key gaps in the literature on Industry 4.0 and supply chain management, this study advances theoretical development and informs more effective digital transformation strategies for contemporary supply chains.

LITERATURE REVIEW

The concept of resource orchestration bridges a crucial gap in strategic management by focusing on the fundamental role of managers in identifying, collecting, and deploying resources to generate new assets. Individually, these assets do not inherently confer a competitive advantage unless strategically integrated and utilized (Sund et al., 2018; Xu & Pero, 2023). Within this framework, resource utilization refers to the deliberate application of capabilities to achieve a competitive edge, whereas resource bundling involves the integration of diverse resources to develop new competencies

(Kamasak, 2017). Resource Orchestration Theory (ROT) posits that organizational leaders must proactively manage supply chain resources to facilitate the adoption of SC4.0, with the objective of enhancing coordination and integration—key enablers of lean practices across the supply chain (Sirmon et al., 2011; Ljungkvist et al., 2023; Xu & Pero, 2023). The structuring process encompasses both the acquisition of new resources and the evaluation of existing ones, while bundling activities include pioneering (developing novel capabilities), enriching (strengthening existing capabilities), and stabilizing (gradually reinforcing SC4.0 adaptability resources) (Sirmon et al., 2011).

The Resource-Based View (RBV), an evolution of traditional resource-based theory, integrates key insights from relational network theory to better understand how inter-organizational relationships contribute to sustained competitive advantage. This perspective emphasizes the role of collaboration within business networks, where the sharing of resources and capabilities among partner organizations leads to a competitive position that is difficult to imitate (Hemmati et al., 2016; Holdford, 2018; Kodua, 2019b). RBV is particularly useful for explaining how lean practices at the supply chain level foster the exchange of knowledge, skills, and resources among partners, thereby enhancing overall performance and long-term competitiveness. Recent research (Ahmed, 2022; Piotrowicz et al., 2022) further supported this perspective.

Previous studies emphasize the critical role of adaptability in modern supply chains, particularly in the context of integrating Industry 4.0 technologies. These studies demonstrate how adaptable supply chains enhance SC4.0 maturity and assess the advantages of deploying technologies such as blockchain and additive manufacturing (Dubey et al., 2018; Yang et al., 2022). A lean supply chain, in this regard, is characterized by a network of interconnected organizations that coordinate the flow of goods, services, information, and financial resources both upstream and downstream. These organizations collaborate strategically to reduce waste and costs while efficiently responding to customer demands (Dias et al., 2022; Piotrowicz et al., 2022, 2023).

Hypotheses development

The impact of SC4.0 adaptability on lean supply chain management

The exploration of SC4.0 entails the integration of a suite of Industry 4.0 technologies, including cloud computing, big data analytics, the Internet of Things (IoT), virtual reality (VR), augmented reality (AR), and artificial intelligence (AI). Emerging research indicates that these technologies are highly compatible with the principles and objectives of Lean Supply Chain Management (LSCM) (Merino et al., 2020; Dias et al., 2022). While each technology contributes uniquely, studies have identified IoT, big data, and cloud computing as having the most substantial impact on LSCM. For example, cloud computing facilitates key LSCM outcomes by enhancing cost-efficiency and optimizing the use of resources (Merino et al., 2020; McDermott et al., 2024).

Virtual reality (VR) in LSCM helps in understanding complex processes involving multiple participants (Li et al., 2018). Tortorella et al. (2018) highlighted VR's ability to significantly reduce product development costs and shorten time-to-market. Raji et al. (2021) further illustrated how VR can impact lean value stream design, while Rossini et al. (2019) demonstrated its usefulness in identifying production issues by simulating production setups, ultimately enhancing production systems and providing visual insights. These findings align with the views of previous researchers (Dubey et al., 2018; Leong et al., 2020), who suggested that "without the integration of new technologies with existing practices, technological advances may fail to meet market needs." To maximize the benefits of SC4.0, managers must strategically orchestrate and manage ambidextrous supply chain resources—balancing the exploration of innovative technologies with the exploitation

of existing capabilities—to improve coordination and minimize waste. Consequently, both SC4.o exploration and exploitation are essential for effective LSCM implementation. Based on this reasoning, the following hypothesis is proposed:

H1: SC4.o adaptability has a direct positive effect on LSCM implementation.

Lean supply chain management and firm's operational performance

We hypothesize that LSCM implementation will positively improve the operational performance of the focal firm, as evidenced by lower costs, increased inventory turnover, and reduced cycle times. However, the existing literature presents mixed findings on this relationship (Dias et al., 2022; Buendia et al., 2023), likely due to the diverse methodological approaches employed in assessing LSCM practices. Despite these inconsistencies, we align with studies that demonstrate a positive association between LSCM and improved operational outcomes (Chu et al., 2021; McDermott et al., 2024). Prior research (Buendia et al., 2023b; Leong et al., 2020; Tortorella et al., 2018) emphasized that the core objective of LSCM is to enhance operational efficiency, particularly in product delivery, by facilitating resource exchange, streamlining workflows, and embedding continuous improvement strategies throughout the supply chain. Standardizing processes and products within Process and Product Standardization, as fundamental principles of LSCM, reduces variability and contributes to cost savings. Moreover, the integration of LSCM practices is shown to reduce cycle times and improve overall supply chain efficiency (Fuentes et al., 2020b).

Effective supply chain planning significantly enhances the focal firm's performance by reducing production costs, improving inventory turnover, and shortening cycle times. These outcomes stem from forecasting customer demand and focusing on current market segments (Buendia et al., 2023b; Rossini et al., 2019). Moreover, the incorporation of buffer queues within production sub-processes helps absorb demand variability and mitigate uncertainties related to production lead times (Fuentes et al., 2020b). Therefore, the following hypothesis is proposed:

H2: LSCM has a positive effect on firms' operational performance.

The mediating role of lean supply chain management applications in the relationship between SC4.o adaptability and firm's operational performance

LSCM implementation can serve as a strategic mechanism through which firms leverage the dynamic capabilities embedded in SC4.o adaptability (Sirmon et al., 2011; Carney et al., 2019) and the capabilities these technologies generate. Rooted in Resource Orchestration Theory (ROT), this perspective emphasizes the critical link between resources, strategic outcomes, and performance (Sirmon et al., 2011; Holdford, 2018; Kodua, 2019a). LSCM plays a pivotal role in orchestrating resources effectively, thereby positioning the firm to extract value from SC4.o flexibility. Simultaneously, SC4.o adaptability provides a strategic direction for mobilizing both internal and external supply chain resources, facilitating supply chain cohesion and enabling the operationalization of this integrative capability—referred to as supply chain unity (Zeng et al., 2017; Zeng & Khan, 2019).

In this context, LSCM enables firms to access and mobilize external supply chain resources by fostering collaboration, strategic partnerships, and cohesion among supply chain stakeholders, thereby contributing to waste reduction and cost efficiency (Iyer et al., 2019). The RBV theoretical model (Kodua, 2019a) offers a theoretical lens through which to understand how LSCM enhances

operational performance (Fuentes et al., 2020b). Prior research suggests that LSCM—by promoting flexibility—serves as a mediating mechanism between supply chain resource availability and the operational efficiency of the focal firm (Maqueira et al., 2021). Consequently, the integration of emerging Industry 4.0 technologies with existing internal assets (i.e., mature digital capabilities) becomes increasingly valuable when these are synergistically combined with the external resources of supply chain partners through LSCM. This strategic alignment generates compounded performance benefits. Moreover, the LSCM leveraging strategy is difficult to replicate due to lean management creating valuable, rare, hard-to-duplicate, and non-substitutable capabilities (Mensah et al., 2020).

In simpler terms, LSCM provides unique benefits to supply chain partners when supported by SC4.0 adaptability. These benefits include cost reduction, increased sales, and shorter cycle times. From a relational standpoint, LSCM has been shown to improve the internal efficiency of the focal firm (Fuentes et al., 2020b; Buendia et al., 2023b). Building on these insights, the following hypothesis is proposed:

H3: LSCM mediates the relationship between SC4.0 adaptability and firms' operational performance.

To examine the proposed ideas, the following estimation model is applied.

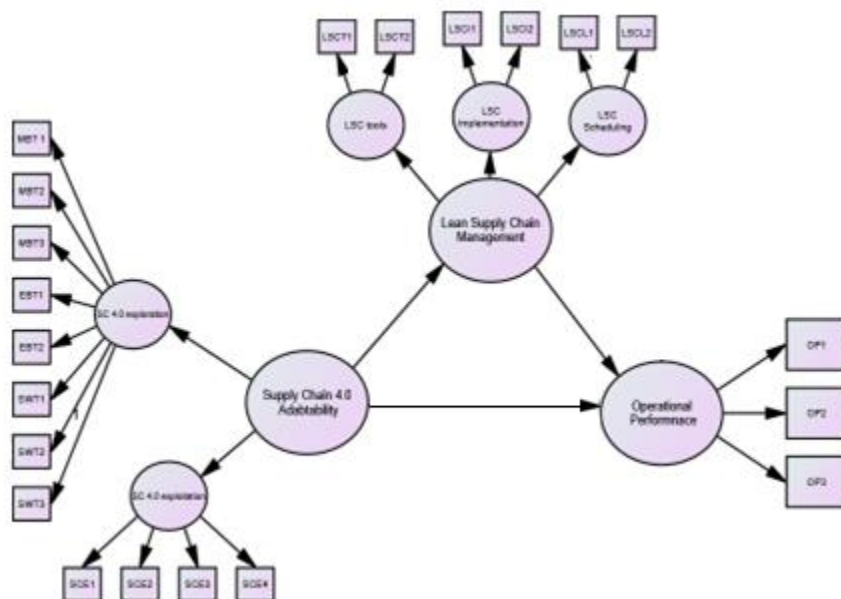


Figure 1. Theoretical model

RESEARCH METHOD

Data collection was conducted using a computerized system in which the contact information of potential respondents was randomly displayed to trained interviewers. This method facilitated efficient appointment scheduling and enabled immediate digital recording of responses (Hair et al., 2014). Interviewers underwent specialized training to ensure the reliability and consistency of the data collected. To further ensure data quality, a supervisor periodically monitored live interviews,

and the authors independently evaluated interview quality on the first day of data collection. Midway through the data collection phase, a web-based questionnaire was introduced to reach participants who had not yet responded. This questionnaire underwent content validation by a panel of five experienced supply chain management scholars. A pilot study involving five supply chain management leaders was then conducted to confirm the clarity and comprehensibility of the questionnaire items. The methodological rigor applied in the development and administration of the instruments ensures transparency and replicability for future research.

The research survey targeted professionals holding leadership roles in supply chain management, logistics, or operations management within selected locations, focusing on SC4.0 implementation, lean supply chain management (LSCM), and key company performance indicators. In other regions, the survey was directed at leaders in information systems management, emphasizing their involvement in SC4.0 exploration (Podsakoff et al., 2003). The final sample consisted of 197 medium-sized automotive companies in Indonesia that met the eligibility criteria and were included in the subsequent analysis.

Covariance-based structural equation modeling (CB-SEM) was employed to test research hypotheses, using EQS 7.0 software. SEM requires the evaluation of the measurement model, which was conducted through both exploratory and confirmatory factor analyses. The standardized load values of the scale items were confirmed to be above 0.5. After performing exploratory and confirmatory factor analysis with SPSS software (v. 26) and EQS 7.0 software, covariance analysis was conducted to verify the impacts and relationships among the structural model variables (Hair et al, 2014). We also examined how well the model fits to assess the accuracy of the model data. To ensure strong results, the PROCESS tool for SPSS was used to conduct an additional mediation study with the bootstrapping method (Preacher & Hayes, 2004), which measured the significance of the indirect effect. Bootstrapping generated a sampling distribution of the indirect effect to obtain confidence intervals (CIs) through resampling with replacement. An indirect effect was considered statistically significant if the corresponding CI did not include zero.

RESULTS

Content validity was ensured by employing previously validated measurement scales and a survey instrument reviewed by a panel of prominent supply chain management (SCM) experts. A hierarchical factor structure was adopted, comprising three levels: a first-level factor to assess the operational performance of the main company, a second-level factor to evaluate LSCM, and a third-level factor to measure SC4.0 adaptability. Initially, a basic factor analysis was performed to assess the scale's unidimensionality and reliability. The unidimensionality of the constructs was supported by eigenvalues greater than one, standardized factor loadings above 0.5 (with the exception of one item, LSCS3, in LSCScheduling), satisfactory explained variance for each factor, and high chi-square/degrees of freedom values in Bartlett's sphericity test ($p < 0.05$). Reliability was assessed using Cronbach's alpha, with scores of 0.6 or above considered acceptable, consistent with established literature (Leong et al., 2020) and recent studies in SCM (Kauppi & Luzzini, 2022). Composite Reliability Index was then assessed for various factors, including main base technologies (0.912), extra base technologies (0.887), smart work and production technologies (0.91), SC4.0 exploitation (0.813), lean supply chain tools (0.880), lean supply chain implementation (0.832), lean supply chain scheduling (0.781), and operational performance (0.773). All exceeded the accepted threshold of 0.7, demonstrating reliability. Table 2 presents the results of the exploratory factor

analysis and the details of observable variables. Items with standardized loadings below 0.5, marked with an asterisk, were removed following exploratory factor analysis and reliability analysis.

The average variance extracted (AVE) values for all constructs exceeded the minimum threshold of 0.50, indicating adequate convergent validity. Specifically, AVE values were as follows: main base technologies (0.8209), extra base technologies (0.7881), smart work and production technologies (0.8214), SC4.0 exploitation (0.7620), lean supply chain tools (0.7750), lean supply chain implementation (0.7273), lean supply chain scheduling (0.6651), and operational performance (0.5871). Discriminant validity was established if the squared average variance extracted for each factor—obtained through exploratory factor analysis using SPSS—was greater than its shared variance (correlation). Confirmatory factor analysis (CFA) using covariance-based structural equation modeling (CB-SEM) was applied to evaluate all elements in the final measurement model (refer to Table 1) and to assess the multidimensional structure of the two second-order constructs (SC4.0 exploration and LSCM exploitation) and the third-order construct (SC4.0 adaptability). The final measurement model, along with the second- and third-order constructs, showed satisfactory fit values.

Table 1. Exploratory and confirmatory factor analysis

Factor	Variable	CFA	EFA	Cronbach's alpha	Explained variance (%)
Supply chain 4.0 exploration Main base technology	MBT1. Infrastructure as a service	0.790	0.891	0.912	82.091
	MBT2. Software as a service	0.891	0.923		
	MBT3. Platform as a service	0.873	0.902		
Extra base technology	EBT1. Big data	0.744	0.885	0.887	78.81
	EBT2. Internet of Things	0.755	0.882		
Smart work and production technology	SWT1. Virtual reality	0.873	0.921	0.913	82.14
	SWT2. Expanded reality	0.902	0.922		
	SWT3. Artificial intelligence	0.802	0.892		
Supply chain 4.0 exploitation	SCE1. To remain competitive, our supply chain supervisors center on lessening operational redundancies in our existing forms	0.601	0.752	0.813	76.20
	SCE2. Leveraging our current supply chain innovations is critical for our firm's methodology	0.672	0.772		
	SCE3. To remain competitive, our supply chain directors center on progressing our existing advances	0.823	0.856		
	SCE4. Our directors center on creating more grounded competencies in our existing supply chain forms	0.848	0.866		

Factor	Variable	CFA	EFA	Cronbach's alpha	Explained variance (%)
Lean supply chain management	LSCT1. Esteem stream mapping is utilized to recognize and dispose of squander all through our supply chain	0.673	0.876	0.880	77.51
	LSCT2. Our supply chain employs incline fabricating methods (Kanban Frameworks and setup time decrease)	0.852	0.876		
Lean supply chain implementation	LSCI1. Our supply chain creates a high stock turnover and limits the stock	0.624	0.851	0.832	72.73
	LSCI2. Process and product standardization is a common practice in our supply chain	0.643	0.851		
Lean supply chain scheduling	LSCS1. Our supply chain performs long-term predictions of customer demand and strictly targets current market segments	0.671	0.821	0.781	66.51
	LSCS2. In our supply chain, the plan for managing uncertainty includes using queues and buffers to shield sub-processes	0.467	0.812		
	LSCM3. Our supply chain framework rarely changes		*		
Operational performance	OP1. Cost of manufacturing	0.547	0.748	0.775	58.71
	OP2. Inventory turnover	0.675	0.751		
	OP3. Time taken (from materials to delivery)	0.647	0.791		

Note : *item removed following confirmatory factor and reliability analysis

CB-SEM was employed to assess the structural model. The initial step involved assessing the model's stability. With a total of 40 parameters estimated, the subject-to-parameter ratio exceeded 5:1, thereby meeting the minimum threshold recommended for stable model estimation (Hair et al, 2014). To evaluate the model's goodness-of-fit, an analysis was conducted based on the indicators and recommended values outlined by Hair et al (2014). The results are presented in Table 2.

Table 2. Results of goodness of fit analysis

RMSEA	GFI	AGFI	NFI	NNFI	CFI	IFI	X ²	df	X ² /df
0.055	0.875	0.904	0.802	0.856	0.912	0.915	300.26	180	1.67

The overall fit of the model was evaluated with RMSEA (0.055) and GFI (0.875), both indicating an acceptable model fit. Incremental fit indices further supported the adequacy of the model, with all values exceeding recommended thresholds: AGFI = 0.904, NFI = 0.802, NNFI = 0.856, CFI = 0.912, and IFI = 0.915. Model parsimony was also confirmed, with a normed chi-square value of 1.67, which fell within the acceptable range. These results collectively suggest that the model exhibits a

good overall fit, supporting its robustness and aligning with previous findings in supply chain research (Leong et al., 2020; Maqueira et al., 2021; Oliveira-Dias et al., 2022; Yang et al., 2022).

The study's findings support all proposed hypotheses, confirming their statistical and theoretical validity. SC4.o adaptability demonstrates a strong positive influence on the adoption of LSCM, with a path coefficient of 0.752 ($p < 0.001$). Thus, H1 is supported, explaining 55.8% of the variance in LSCM. This suggests that the synergistic effects of SC4.o exploration and exploitation significantly contribute to the implementation of LSCM practices. Additionally, LSCM also has a significant effect on operational performance, with a path coefficient of 0.46 ($p < 0.001$). Therefore, H2 is accepted, accounting for 27.2% of the variance in operational performance. This result contributes to the ongoing debate in the literature about the relationship between LSCM and operational performance (Buendia et al., 2021; Piotrowicz et al., 2023).

Following the methodology of Yang et al. (2022), the total effect of one variable on another was decomposed into its direct and indirect components. A significant indirect effect indicates that a substantial portion of the relationship between the dependent and independent variables is mediated by the intervening variable. The indirect effects analysis confirms H3, showing that operational performance is positively influenced by SC4.o adaptability through LSCM ($\lambda = 0.313$, $t = 2.451$). This result underscores the central role of LSCM in mediating the relationship between SC4.o adaptability and operational performance. To further evaluate the mediating effect of LSCM, the direct path from SC4.o adaptability to operational performance was examined. The result ($\lambda = -0.062$) reveals no significant direct relationship, suggesting that the connection between SC4.o adaptability and operational performance is fully mediated by LSCM. Additionally, a bootstrapping procedure with 10,000 replications was employed to validate the significance of the indirect effects. The estimated indirect effect of LSCM is 0.0948, with 95% bias-corrected confidence intervals (CIs) ranging from [0.0391, 0.1672]. These results provide robust empirical support for the mediating role of LSCM in the relationship between SC4.o adaptability and operational performance.

DISCUSSION

This study examines the relationship between SC4.o adaptability, LSCM, and the operational performance of focal firms through the lens of Resource Orchestration Theory (ROT) and the Resource-Based View (RBV). The findings confirm that SC4.o adaptability significantly enhances LSCM implementation, highlighting the critical role of balancing exploration and exploitation in supply chain operations. This result underscores that LSCM, which facilitates the adoption of lean principles, is most effectively implemented when organizations strike an optimal balance between leveraging existing capabilities and integrating innovative technologies during the transition to SC4.o. We position LSCM as a mechanism that enables both exploration and exploitation. As Tortorella et al. (2018) argued, exploration within supply chain management fosters new knowledge and ideas, but these ideas only generate value once they are exploited—selected, implemented, and operationalized. Thus, firms must navigate this duality to avoid inefficiencies stemming from over-reliance on either exploration or exploitation, ensuring a stable and optimized SC4.o transition.

The finding aligns with previous research on operations management, reinforcing the benefits of supply chain flexibility (Buendia et al., 2023b) and the synergy between LSCM and Industry 4.0 technologies (McDermott et al., 2024; Dias et al., 2022). Furthermore, by extending the analysis of Industry 4.0, lean management, and adaptability to the supply chain level, this study contributes to the growing body of research on how these elements interact to create value within supply chains. This broader perspective enhances theoretical understanding while providing actionable insights for firms seeking to optimize their digital transformation strategies.

Additionally, the study demonstrates that LSCM implementation directly improves operational efficiency, reinforcing its relevance as firms transition to SC4.0. Our findings remain significant across industries, supply chain structures, and technological contexts, supporting previous research that links lean practices to enhanced performance outcomes (Buendia et al., 2021; Bravo et al., 2023; Tortorella et al., 2020).

Importantly, this study also provides empirical support for ROT by demonstrating that SC4.0 flexibility indirectly enhances operational performance through LSCM. This finding aligns with Buendia et al. (2023a), who identified LSCM as a key mediator in improving business efficiency. By clarifying inconsistencies in the literature regarding the relationship between IT investments and performance, our results contribute to a deeper understanding of how firms can effectively leverage digital transformation. Furthermore, the finding supports the RBV perspective (Kodua, 2019b), which asserts that firms can achieve a sustainable competitive advantage by optimizing internal resources, minimizing costs and waste, and leveraging external collaborations through LSCM. This integrated approach strengthens operational performance, positioning firms for long-term success.

However, our findings also indicate that simply adopting new Industry 4.0 technologies or optimizing existing internal resources does not automatically translate into superior operational performance. Instead, firms must integrate both internal and external resources to unlock competitive advantages—a conclusion consistent with Buendia et al. (2023b). This underscores the necessity of strategic resource orchestration, emphasizing that digital transformation alone is insufficient; rather, success depends on the effective alignment of lean practices, technological adaptability, and collaborative supply chain networks.

By bridging gaps in the literature and offering practical insights for firms navigating Industry 4.0 adoption, this study contributes to both theoretical advancements and managerial decision-making. The results emphasize the need for a nuanced approach to SC4.0 flexibility, demonstrating that LSCM serves as a critical enabler in achieving sustainable operational excellence.

CONCLUSION

This study makes several significant contributions to the existing literature on SC4.0 adaptability, LSCM, and operational performance. First, to the best of the authors' knowledge, this research represents one of the first attempts to develop a robust measurement instrument for SC4.0 adaptability, addressing a critical gap in supply chain management research. Second, it is among the few studies that examine the key factors influencing LSCM implementation, with a particular focus on SC4.0 ambidexterity—highlighting the need for organizations to balance exploration and exploitation in their digital transformation efforts. Third, this study builds upon previous findings that have demonstrated the importance of LSCM deployment in enhancing firm performance, further reinforcing its role as a critical enabler of supply chain efficiency.

Moreover, this research provides empirical evidence of LSCM's full mediating role in the relationship between SC4.0 adaptability and operational performance, offering deeper insights into how firms can effectively leverage Industry 4.0 technologies for competitive advantage. Additionally, our findings validate the applicability of both the Resource-Based Relational View and Resource Orchestration Theory (ROT) in explaining supply chain management dynamics, particularly in the context of LSCM implementation. These theoretical underpinnings align with prior research (Buendia et al., 2021; Dias et al., 2022), further strengthening the argument that LSCM serves as a crucial mechanism for optimizing SC4.0 capabilities.

The findings of this study hold important implications for both scholars and practitioners. Academically, this research contributes to the theoretical discourse on supply chain adaptability and

digital transformation by introducing a novel framework for evaluating SC4.0 adaptability. From a managerial perspective, the insights provided can guide firms in strategically implementing LSCM to maximize the benefits of Industry 4.0 technologies. By addressing key research gaps and offering practical recommendations, this study advances both theory and practice in the field of supply chain management.

MANAGERIAL IMPLICATION

This study offers valuable insights for supply chain managers navigating the transition to Industry 4.0 (I4.0). First, it introduces the concept of SC4.0 adaptability and proposes a practical measurement framework, addressing a key challenge in supply chain transformation. By demonstrating the effectiveness of this measurement approach, the study provides managers with a structured method to assess their organization's readiness and responsiveness to SC4.0, aligning with the growing need for adaptive strategies in digital supply chains (Dubey et al., 2018; Leong et al., 2020).

Second, the study highlights that SC4.0 adaptability alone does not directly enhance a company's operational performance. Instead, performance improvements emerge when SC4.0 adaptability is leveraged through LSCM. This finding has significant implications for supply chain professionals, as it underscores the necessity of integrating lean principles with digital transformation efforts. Managers should recognize that achieving SC4.0 adaptability is only the first step—realizing its full potential requires embedding LSCM practices across the supply chain.

To facilitate this integration, supply chain leaders must ensure that all supply chain participants adopt lean methodologies internally. A phased approach is recommended: first, the focal firm should provide technical and strategic support to its supply chain partners, enabling them to implement lean practices effectively. In the second phase, firms should prioritize SC4.0 adaptability across the supply chain to foster the collaborative capabilities required for LSCM implementation.

Additionally, the findings emphasize the role of supply chain leaders in orchestrating both internal and external resources to optimize I4.0 adoption. Managers must proactively align their digital transformation strategies with lean management principles, ensuring that supply chain partners are equally prepared for this shift. By fostering synergy between SC4.0 adaptability and LSCM, firms can enhance supply chain efficiency, agility, and overall performance.

Ultimately, expanding the supply chain's capacity for adaptability is crucial for executing an ambidextrous strategy—one that balances the exploration of new technologies with the efficient utilization of existing capabilities. This approach enables firms to maximize the benefits of SC4.0 while maintaining operational stability and achieving long-term competitive advantages.

LIMITATION AND FUTURE RESEARCH

This study has several limitations that should be acknowledged. First, the research was conducted using respondents from Indonesia, meaning that cultural and regional factors may have influenced their perceptions. Since businesses in different countries with distinct cultural contexts may exhibit varying preferences for exploration and exploitation, the generalizability of these findings may be limited. However, given the similarities in cultural traits between Indonesia and other emerging economies, the results may still offer relevant insights for regions with comparable business environments. Future research should validate the proposed model using data from diverse

countries to better understand global supply chains and identify potential differences between exploratory and exploitative companies.

Second, the study employed a cross-sectional research design, which limits its ability to capture the dynamic nature of SC4.0 adaptability and LSCM over time. To strengthen the robustness of these findings, future research should adopt a longitudinal approach to track the evolution of SC4.0 integration and its long-term effects on operational performance.

Third, while the response rate in this study is comparable to other research in operations management, a higher participation rate would enhance the reliability and generalizability of the findings. Future studies should aim to increase response rates through targeted engagement strategies to ensure broader representation across industries and supply chain actors.

Additionally, the proposed measurement scale for SC4.0 adaptability requires further validation. Its effectiveness depends on adoption by other researchers, making it essential for future studies to refine and test this scale in different contexts. Moreover, this study assessed operational performance using subjective measures, which may introduce potential biases. Future research should incorporate objective, quantitative data from secondary sources to validate and strengthen the findings.

Furthermore, as Industry 4.0 technologies continue to evolve, future research should revisit and replicate this study once these technologies have become more mature and widely adopted. Examining SC4.0 adaptability at different stages of technological advancement could provide deeper insights into its evolving impact on supply chain management. Another promising avenue for future research is investigating moderating variables such as IT capabilities, organizational culture, and leadership competencies, which could further clarify the relationship between SC4.0 adaptability, LSCM, and operational performance. Finally, exploring the mediating role of supply chain resilience in the relationship between Industry 4.0 adoption and LSCM would contribute to resolving ongoing debates about the long-term impact of digital transformation on lean supply chain practices. By addressing these research gaps, future studies can enhance our understanding of how firms can effectively navigate the intersection of Industry 4.0 and lean management principles, ultimately leading to more resilient and high-performing supply chains.

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