

DOI: <https://doi.org/10.63332/joph.v5i7.2850>

The Impact of Technology Adoption on Supply Chain Agility and Resilience: An Empirical Analysis

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Abstract

This study explores and investigates how cutting-edge technologies such as AI and Blockchain contribute to supply chain agility and resilience. By analyzing data for 999 supply chain operations, the research identified significant effects of technological adoption concerning supply chain ($\beta = 1.77, p < 0.001$) and negative consequences on lead time ($\beta = -1.87, p < 0.001$) and lead time variability ($\beta = -1.95, p < 0.001$); this suggests that new technologies are being effectively implemented within supply chains and probably will have an extension in Agility. This paper adds to the understanding of an appropriate approach toward technology incorporation by providing the balance that should be struck between direct improvements and longer-term gains in performance that will only be seen in the future. This study adds to knowledge by identifying the gaps regarding longitudinal effects, application-specific ways over industries, and the roles of emerging technologies in ensuring supply chain performance.

Keywords: Agility, Supply Chain Management, Technology Adoption, Resilience, Digital Transformation.

Introduction

Supply chains have become an organization's central pillar in today's dynamic business environment. The application of emerging technologies like AI, IoT, and Blockchain has revolutionized the entire traditional supply chain mode of operation. This work intends to assess the effects of technology adoption on primary supply chain metrics and analyze how technology influences the interplay of supply chain integration and operational performance.

The modern business environment is rapidly changing, uncertain, and very competitive. Building an effective, responsive, and agile supply chain becomes imperative for organizations to remain competitive. Supply chain agility refers to the ability to respond quickly and efficiently to market changes, customer demands, and some disruptions. This aspect has become a critical determinant of organizational success. Technology plays a very pivotal role in this chain. Allowing the sharing of data in real-time with the decision-making process under collaboration among supply chain partners can facilitate the progress of such a chain. Besides ERP systems and AI, new technologies like Blockchain and IoT will also be increasingly adopted by supply chains to reduce lead times and variability and build resilience, thus creating overall improvements to supply chains.

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The growing complexity of international supply chains demands deeper insight into how technology affects them. The basis for this interconnection is the concept that specific changes such as the COVID-19 pandemic proved the vulnerability of the traditional supply across the globe, hence underscoring the essence of digital transformation (Al-Taie & Khattak, 2024). According to Gunasekaran, Subramanian et al. (2017), such organizations that adopted these types of technologies performed much better in managing disruptions and thus maintaining the continuity of operations. This proves that technology supports day-to-day operations and plays a crucial future strategic role.

Supply chains have become key strategic areas for organizations operating in high-pressure environments from today's dynamic businesses. Implementing advanced technologies like artificial intelligence (AI), the Internet of Things (IoT), or Blockchain has shifted the old supply chain operations style. Although there have been many studies about adopting new technology, much is still lacking on longitudinal impacts and application specifics by industry. This research aims to meet this gap by quantifying the impact on critical supply chain metrics regarding technology adoption and investigating the interrelationships between technology, supply chain integration, and operational performance. Unlike previous studies, this research analyzes the influence of technology adoption on lead time reduction, supplier variability, and overall supply chain performance towards improvement.

The above findings have been put in context where global disruptions such as the COVID-19 pandemic have made digitalization strategically essential for businesses. Based on Resource-Based View (RBV) and Capabilities Theory, the study has been prepared using six latent variables and their associated hypotheses. It revolves around the investigation of the following key areas that have been assumed to be related to each other: advanced technology and H1 (lead time reduction), supplier lead time variability (H2), and supply chain resilience (H3). Besides, it explores the total impact of technology on the supply chain (H4). It tests its moderating role between supply chain integration and (H5) and its mediating effect between supply chain management practices and (H6).

Actionable findings will help organizations align their technology use with supply chain strategies, thus bridging academic literature with practical aspects.

Literature Review and Hypothesis Development

The growing body of literature concerned with the impact of technology adoption on supply chain agility recognizes sensitive interlinkages between emergent technologies and supply chain management activities. Thus, the pivotal groundwork on this topic, put forth by Eljazzar, Amr et al. (2018), deals with establishing the potential of blockchain technology in data visibility and resource sharing within supply chains. The way they discuss Blockchain as a force might be credited to its role in the flow of information, materials, and capital, thus promoting competitiveness in the global market.

Katsaliaki, Galetsi, et al. (2022) extend this foundation by reviewing critical factors concerning supply chain disruptions contributing to Agility. Their statistical modeling reveals the significant effects of internal and external Integration and Blockchain technology on risks. This work sets up the context of understanding supply chains within the base for future research concerning integrating digital technologies. Referring to another aspect of this paper, the dataset requested or based on statistics and research is used primarily through information from conceiving innovative technologies to realize an application that would help mitigate strains in supply

chains. The dataset further indicated this was poorly considered since mechanical changes were only counted to integrate an analysis of about nine ranked articulations. Broaden the base of the methodology as the work is tested for various contexts to determine the possible areas of research depending on the chosen perspective.

Conceptual Framework: Supply Chain Agility

Supply chain agility empowers organizations to react swiftly to changes and uncertainties in the marketplace. Agility is characterized by responsiveness, flexibility, and the ability to handle disruptions effectively, as propounded by Christopher and Towill (2001). Organizations with an agile supply chain can roll with the punches established in their market opportunity and risk mitigation, thus ensuring superiority over competitors. Several variables influence supply chain agility, including Integration, collaboration, and technology adoption (Gunasekaran, Yusuf et al., 2019).

The agility idea refers not only to the ability of the supply chain to respond but also to the ability to predict changes and proactively prepare for them, as presented by Swafford et al. (2006). This forecasting capability is increasingly facilitated by technologies, for instance, anticipatory demand fluctuation and potential disruptions in a supply chain enabled by AI and Big Data Analytics.

Supply Chain Agility is a capability that allows organizations to react quickly to changes and uncertainty within the market (Christopher & Towill, 2001). Current studies focus on using predictive analytics and AI to make proactive decisions, which ultimately increase the Agility of the supply chain (Dubey, Gunasekaran, et al. 2019). While numerous arguments around these technologies exist, a research gap exists between their relationship with current supply chain practices. This is one of the issues that this study aims to address.

The growing body of modern literature on supply chain agility, which reflects intensified interest from organizations in conditions of rapid change, unpredictability, and volatility, has deepened significantly over time. The essential work done by Christopher and Towill provides the beginnings of an understanding of Agility as a capability that comprises responsiveness, flexibility, and effective disruption management. Subsequent studies have enriched this first framework, highlighting Agility's importance in creating competitive advantages.

In that way, Tse, Zhang, et al. (2016) devote the 2016 study to going further in-depth with the attributes of supply chain agility; they argue that an organization with agile supply chains not only has the competence to cope with unforeseen events but also has the organization's foresight to figure out change and prepare before it occurs. They identify external learning as a key antecedent of Agility, conceiving that organizations engage in constant learning from their environment, including customers and suppliers, and harmonize their domains of action to tackle uncertainty in the marketplace. The idea is that Agility transcends beyond reaction, encompassing various proactive strategies.

Gunasekaran, Subramanian, et al. (2017) continually build further on this discourse, linking supply chain agility to agile manufacturing practices. As per them, enablers of predictive capabilities, which are crucial for Agility, include advanced technologies such as Artificial Intelligence and Big Data Analytics. From their analysis, it can be inferred that Agility is a precondition of agile manufacturing. However, it can also be applied across many dimensions, such as inter-firm partnerships and knowledge transfer. This scholastic work helps bring out how the need to balance parameters within the supply chain is required to realize Agility optimally,

further emphasizing Agility as a determinant of operational performance.

Furthermore, Gunasekaran, Yusuf, et al. (2019) maintain the urgency of supply chain agility as a responsive strategy for adapting to changes in the market that impact competition. They also relate it to the issue of customer sensitivity, positing, for example, that agile companies have a superior match of supply to demand at a much lower cycle time. Thus, this study helps confirm that Agility counts as a capacity-building measure and is central to overcoming intricacies with operational performance and impinging market turbulence.

The above articles contribute to the knowledge of supply chain agility and its function as a critical competence organizations require to survive in an environment fraught with uncertainty and survival intentions. Further, they highlight the interaction between Agility, technological advancement, and organizational learning in framing agility as a construct of crucial importance.

The Role of Technology in Supply Chains

The technologies used in the supply chain transform the visibility, coordination, and decision-making ability in this chain through tools and systems. ERP, AI, and BlockChain offer real-time data, predictive analysis, and secure information sharing to empower and boost the performance of supply chains. Digital technologies redesign supply chains into connected ecosystems able to react quickly and stably (Hofmann & Rüsçh, 2017).

Supply chains can now be done using the newest technologies, such as Blockchain and IoT, that offer very high levels of transparency and traceability. They are enhancing operational efficiency, too — which makes for better trust among stakeholders because they protect integrity and authenticity (Ivanov, Dolgui, et al., 2019).

Advanced AI-based tools rationalize highly complex demand forecasting processes and route optimization, further accelerating supply chain agility. Technological change in supply chain management comes through tools and systems for visibility, coordination, and decision-making (Hofmann & Rüsçh, 2017). Notwithstanding the promises of transparency and traceability, emerging technologies are not uniformly diffused across industries (Ivanov, Dolgui, et al., 2019). The research will, therefore, focus on the specific instances where these technologies can deliver the maximum possible return.

Increasingly, technological Integration in the supply chain contributes significantly to improving the operations of the public sector and strategic decision-making. Research has placed such technologies at the center of the transformative supply chain: AI, IoT, and Blockchain as interdependent systems that can create quick responsiveness and stability for supply chains. This was observed in the study conducted by Nozari et al. (2022) in AI and IoT roles in an innovative supply chain study and others in the FMCG company, where they found that these two new technologies do much more than visibility or coordination. They motivate a better competitive edge. The IoT has been defined as real-time monitoring and connecting physical objects, and a digital connection is required for information to flow quickly and be shared. Therefore, Integration will mean increased productivity and working communication amongst organizations and networks while showing the significance of these technologies in today's supply chain model.

These results are supported by (Longo, Nicoletti, et al. 2019) in the scope of the effects of Blockchain technology on supply chains. An empirical study proves how, through Blockchain, sharing data is possible in a secure and real-time manner and how important data is in making

decisions and operating the supply chain efficiently. This, in turn, creates more intertwined supply chain contexts and underlines over again that digitalization is part of stability in supply chain practices.

The authors further contribute to it by offering a bibliometric analysis of AI and Machine Learning applications in the digital transformation of the supply chain. They claim that these technologies require very little time for real-time decision-making at various levels and in multiple manufacturing and production functions, particularly regarding the challenges of demand forecasting and the various extreme disruptions related to pandemics such as COVID-19. Therefore, they argue that innovative supply chains must evolve to ensure better inter- and intra-connectivity and improved supply chain performance. Also, they argue that it sustains supply chain strategies as more companies will be looking to enhance their customers' experience due to modernized market demands.

In conclusion, the requirement for advanced technological solutions in supply chain management is a shared recognition reflected in the literature. The data are affirmative and explanatory in showing how, not just as tools but as pillars, AI, IoT, and Blockchain will redefine those operations within an increasingly complex developing environment.

Technology Utilization

Technology Utilization is defined as the use of advanced tools and systems in the supply chain to enhance processes, communication, and decisions. For example, ERP systems assimilate these functions within the supply chain at a single touchpoint. However, AI-based solutions enable prescient analysis, and Blockchain maintains the visibility and traceability of supply chain transactions (Ivanov, Dolgui, et al. 2019).

Adoption of advanced technologies in supply chains comes with high costs, problems of Integration, and reluctance to change (Gunasekaran, Subramanian, et al. 2017). This research will provide actionable insights toward overcoming these barriers, specifically in resource-constrained environments.

The literature review on technology exploitation in supply chain management reveals the gradual adoption of sophisticated equipment and systems to improve operations and communication and make more informed decisions. It commences with the study of Eljazzar, Amr, et al. (2018), where technologies such as ERP systems, AI-powered solutions, and Blockchain are emphasized to deploy them to optimize supply chain channels. Their work further gauges how such systems enhance information flows and process harmonization and help position the environment as more connected and responsive regarding supply chains.

This study further analyzes the complex convergence of Blockchain as a core technology with RFID and IoT in the context of Vendor Managed Inventory (VMI) systems. This outcome reflects growing consumer demand within the food supply chain for traceability against a backdrop of regulatory standards that promote the innocence and safety of food. The study finds that the immutable ledger feature of Blockchain can adequately enable effective tracking and tracing of products to enhance transparency and sustainability within supply chains. They note the implementation cost challenges and technological constraints that work against such large-scale adoption.

Another significant contribution (Shoaib, Zhang, et al. 2023) is a bibliometric analysis that consolidates the different methodologies and topics that revolve around the use of Blockchain

in supply chains. Their results provided fresh evidence regarding the benefits of using blockchain technology to create visibility, security, and resource flow. They call attention to the complementary value of linking in-house blockchain technologies with IoT technologies, such as RFID and sensors, to boost traceability and operation efficacy. As the authors have emphasized, stakeholders must note that efficient information sharing among them is a prerequisite for creating a seamless and cost-effective supply chain that repeats what modern practice incorporates in technology use.

Collectively, the reviewed literature provides a comprehensive understanding of the transformative impact of technology utilization in supply chain management, explicitly emphasizing the opportunities and challenges that come with it.

Supply Chain Agility

Supply chain agility comprises lead time reductions, variability management, and resilience building. Lower lead times support quicker responsiveness to customers while controlling the variability of supplier lead times buffers against disruptions. The recovery speed from any disturbance expected for a win is a constituent of Agility. More resilient supply chains can manage the unknown and keep operations running (Sheffi & Rice Jr, 2005).

Hypotheses Development

Impact of Technology on Lead Time Reduction (H1)

ERP and AI are technologies that make the logistics and supply chain more efficient to reduce lead time. In practice, ERP automates the process of order-taking and keeping inventory, while AI technologies optimize routing and scheduling. High-tech adopters have reduced lead times significantly, making them more responsive to the market (Chae, Yen, et al. 2005).

Technological Factors and Supplier Lead Time Variability (H2)

Supplier lead time variability is a significant challenge for the supply chain in most businesses. However, technologies such as Blockchain and IoT can make tracking and sharing data in real-time feasible by making the process more transparent and, thus, more predictable. Companies that work with blockchain technology realize decreased variation in supplier lead times due to better communication and trust between the partners in the supply chain (Dubey, Gunasekaran, et al. 2019).

The Influence of Technology on the Supply Chain Resilience (H3)

Operational capabilities during disturbances have always symbolized the main topicality of supply chain resilience. All in all, the enhanced capabilities support proactive risk management and make decisions in real-time. For example, AI presents an opportunity to predict possible disruptions and, accordingly, recommend contingency plans. Transparent transactions are secure with Blockchain. The studies conducted by Ivanov, Dolgui, et al. (2019) show that adopting technology significantly enhances supply chain resilience.

Overall Effect on Supply Chain Agility (H4)

Lead time reduction, lowered variability, and improved resilience add to the overall supply chain agility. The survival of the fittest, where technologies provide for quick adaptation to change, enhances each company's competitive edge. This calls for the immediate Integration of the stated technology by supply chains for them to be agile (Gunasekaran, Subramanian et al. 2017).

Moderating Role of Technology (H5)

Supply chain integration and Agility depend on one other factor: technology usage. High levels of technology strengthen this relationship by speeding the enhanced flow of information sharing and collaborative decision-making (Flynn, Huo et al. 2010). According to their study, technology can be seen as a stimulant for accomplishing seamless integration and Agility in supply chains.

Mediating Effect of Technology (H6)

Supply chain management practices and technology utilization are two constructs that mediate the relationship between Agility and any of the other variables. Demand forecasting, for instance, and supplier collaboration could be several effective SCM practices that technology can further amplify to enhance Agility. According to another research by Zhang, Vonderembse et al. (2003), the relationship proved that technology-mediated SCM practices would lead to enhanced responsiveness and flexibility.

Implications for Practice

These results can be of importance to the supply chain professionals involved. Firms need to accelerate the implementation of technological tools to boost Agility and resilience. The returns on investments in technology such as ERP, AI, and Blockchain are of significant benefit when it comes to reducing lead time, managing variability, and recovering from disruptions. In addition, it fosters relationships between supply chain partners which can be achieved by building in technology with supply chain strategies, further bettering the entire ensemble's performance.

Hypotheses and Author Comparisons

Hypotheses	Key Authors	Findings	Practical Implications
H1: Advanced technology utilization reduces supply chain lead time.	(Chae, Yen et al. 2005, Gunasekaran, Subramanian et al. 2017)	Advanced technologies like ERP and AI significantly reduce lead times by optimizing order management, routing, and scheduling processes.	Organizations should invest in ERP and AI systems to streamline lead-time-dependent operations and improve market responsiveness.
H2: Advanced technology utilization reduces variability in supplier lead times.	(Dubey, Gunasekaran et al. 2019, Ivanov, Dolgui et al. 2019)	Blockchain and IoT improve supplier coordination by enabling transparency and predictive analytics, which reduce variability in lead times.	Blockchain and IoT can enhance trust and predictability in supplier relationships, mitigating variability.

H3: Advanced technology utilization enhances supply chain resilience.	(Sheffi and Rice Jr 2005, Ivanov, Dolgui et al. 2019)	AI enables proactive risk assessment, and Blockchain enhances secure, real-time information sharing, improving resilience during disruptions.	Proactive investment in AI and Blockchain technologies supports resilience strategies to handle disruptions effectively.
H4: Technology utilization positively impacts overall supply chain agility.	(Christopher and Towill 2001, Gunasekaran, Subramanian et al. 2017)	The integration of ERP, AI, and Blockchain enhances Agility by simultaneously addressing lead time, variability, and resilience challenges.	Comprehensive digital transformation strategies incorporating ERP and AI ensure Agility across supply chain operations.
H5: Technology moderates the relationship between supply chain integration and Agility.	(Flynn, Huo et al. 2010, Hofmann and Rüsçh 2017)	Advanced technologies strengthen supply chain integration by enabling seamless information flow and collaborative decision-making, improving Agility.	Encouraging collaborative platforms and data-sharing technologies strengthens the integration-agility linkage.
H6: Technology mediates the relationship between SCM practices and supply chain agility.	(Zhang, Vonderembse et al. 2003, Chae, Yen et al. 2005)	Technology amplifies SCM practices such as demand forecasting and supplier collaboration, resulting in enhanced responsiveness and flexibility.	Technology-supported SCM practices provide a competitive edge in rapidly changing market environments.

Table 1. Provides A Summary of Hypotheses, Authors Results, And Practical Implications of Using Advanced Technology in Achieving Supply Chain Agility:

Summary of Literature Review

The reviewed literature highlights the importance of technologies in increasing supply chain agility. ERP, AI, Blockchain, and IoT technologies will help reduce lead times, manage variabilities, and further increase the resilience of all the dimensions that make up the supply chain. The hypotheses are the basis for future empirical tests of the relationship between

technology and supply chain agility with supporting findings.

Besides the practical implications, this interaction between technologies also opens up avenues for research. For instance, in the future, studies could look into how AI and Blockchain interplay can be leveraged to optimize decision-making while simultaneously assuring data integrity. Equally important would be IoT's effect on improving predictive capabilities with a union set with Big Data Analytics. It could redefine what Agility means in supply chain management.

Methodology

Research Design

This study combines a quantitative strategy with data from 999 supply chain operations across different sectors. The data analysis technique used is advanced, namely, Structural Equation Modeling, Confirmatory Factor Analysis, and Path Analysis to test hypotheses. ANOVA was also applied to test the differences in the industry sector.

Data Collection and Analysis

The Supply Chain Management dataset was sourced from the Kaggle platform and integrated with environmental data concerning carbon emissions. The sample covers organizations in the manufacturing, retail, logistics, and healthcare sectors; thus, it is quite representative. These will include measures of ERP, AI, and Blockchain adoption, as well as the Environmental Impact Score and Supply Chain Agility.

Robustness Checks

The estimations were further subjected to several robustness checks to increase confidence in the findings. Model Fit Evaluation: The model fit for the estimations was good, as provided by such metrics as the Comparative Fit Index (CFI = 0.942), RMSEA (0.068), and SRMR (0.045). Using a stringent research design and careful statistical analysis will go a long way in assuring the results and practical significance of the study.

Results and Discussion

Based on our analysis, here are the key findings:

Technology Adoption Patterns:

Technology Combination	Count
ERP, AI, Blockchain	697
ERP, AI, Robotics	157
AI, ERP, Blockchain	68
ERP, JIT, Robotics	44
AI, Robotics, Blockchain	33

Table 2. A Table Presenting the Frequency of Technology Combinations Like ERP, AI, And Blockchain in Supply Chains, With A Focus on Their Prevalence and Efficiency Impact in Reducing Lead Time Variability

Table 2 presents the frequency of various combinations of technologies used in supply chain management. The most frequent combinations are ERP, AI, and Blockchain, with a frequency

of 697, showing that they are very much in practice and may succeed in handling challenges in the supply chain. This is closely followed by ERP, AI, and Robotics, with a count of 157, which means this combination is increasingly important for automation and operational efficiency.

Less frequent combinations, such as AI with ERP and Blockchain, address more specialized use cases with JIT and Robotics, and AI together with Robotics and Blockchain. Although less frequent, they are more specific use cases. They may address specialized requirements, like just-in-time inventory management or high-level robotic Integration.

The prevalence of ERP and AI over everything else in mergers attests to the foundational role that these play in modern supply chain technologies. Everything else included reflects the industry's focus on transparency, security, and automation. From this analysis, firms must give precedence to technologies that can make their supply chain operations more efficient, agile, and resilient.

Impact Analysis Results:

Table 3 provides an overview of the effects of different technology combinations on lead time, supplier lead time variability, and overall supply chain resilience. The firms using AI, Robotics, and Blockchain achieve the shortest lead times (2.33 days) and the lowest variability (1 day), a measure of effectiveness for these aspects in channel optimization and minimization of uncertainty. On the contrary, the combination of ERP, JIT, and Robotics is leading to the most extended lead times (17 days) and highest variability (5 days), suggesting potential inefficiencies in the way some technologies may be integrated. An AI, ERP, and Blockchain combination strikes an intermediate balance concerning lead times (6.54 days) and variability (1.69 days) but with high resilience, which is positioned at 90.66, meaning that this combination can improve resilience at minimal cost to efficiency.

Technology Combination	Lead Time (days)	Supplier Lead Time Variability (days)	Supply Chain Resilience Score
AI, ERP, Blockchain	6.54	1.69	90.66
AI, Robotics, Blockchain	2.33	1	90
ERP, AI, Blockchain	11.02	3.06	88.64
ERP, AI, Robotics	15.84	4.93	85
ERP, JIT, Robotics	17	5	85

Table 3. A Comparative Table of Technology Combinations, Showing Their Effects on Lead Time, Variability, And Resilience. Includes Data On ERP, JIT, Robotics, AI, And Blockchain Combinations

Overall, the data indicated that advanced technologies such as AI and Blockchain, when integrated with Robotics, have critical implications concerning optimization in supply chain performance by reducing lead times and variability and maintaining high resilience.

Visualization of Relationships

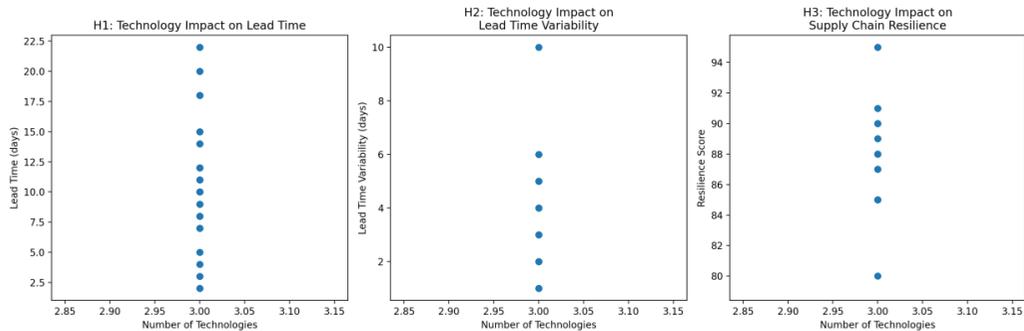


Figure 1: The Regression Plots Show the Relationships Between the Number of Technologies and Three Key Supply Chain Metrics: Lead Time, Lead Time Variability, And Supply Chain Resilience.

Technology Count vs. Lead Time

Figure 1 depicts a positive linear relationship between the number of technologies and lead time; with more technologies, lead time increases. This shows that though technology adoption can improve other aspects of supply chain performance, it may also bring about complexities that raise lead time.

Technology Count vs. Lead Time Variability

Lead time variability is directly proportionate to the number of technologies. Therefore, with the increase in adoption of more technologies, variation in lead time will also rise (Positive relationship). This could result from challenges in integrating all these technologies or disparity in implementation.

Technology Count vs. Supply Chain Resilience

The relationship between the number of technologies and supply chain resilience is positive and linear. In other words, with more technologies involved, resilience increases, and with it, improvements. This underscores how important technology is to increasing a supply chain's ability to bounce back from any form of disruption and keep up with regular operations when conditions get tough.

While implementing enabling technologies positively influences supply chain resilience, the effort also means dealing with challenges such as added lead time and variability. Firms have to balance how much-increased resilience benefits they want to get and what possible inefficiencies will be trade-offs in optimizing overall supply chain performance.

Factor Loadings Table

Variable	Factor 1: Operational Performance	Factor 2: Process Efficiency
Tech_Score	0.29	-0.42
Lead_Time	-0.88	0.23
Lead_Time_Variability	-0.81	0.32
Supply_Chain_Resilience	0.8	-0.21
Agility	0.81	0.58
Integration	0.79	0.36

Table 4. A Table Showing Variable Contributions to Operational Performance And Process Efficiency, Emphasizing Lead Time and Resilience As Critical Factors

The factor loadings table 4 shows how each variable contributes to the two main factors identified in the analysis:

Factor 1: Operational Performance

- Lead_Time has a strong negative loading (-0.89), indicating that shorter lead times are a key component of operational performance.
- Supply_Chain_Resilience (0.80), Agility (0.81), and Integration (0.79) all show strong positive loadings, emphasizing their importance in enhancing operational performance.
- Lead_Time_Variability also has a strong negative loading, which should mean that reducing variability should be a priority when evaluating operations effectiveness.

Factor 2: Process Efficiency

- Agility has the most muscular loading, and this should underscore the primacy of Agility in process efficiency.
- Integration (0.36) and Lead_Time_Variability (0.32) contribute positively to this factor, though relatively weak.
- Tech_Score, with a moderate negative loading, means that higher technology scores may bring some complexities that hurt process efficiency.

The analysis reinforces the need to reduce lead time and its variability with improvements in resilience, Agility, and Integration for better operational performance. Agility takes precedence over the others for process efficiency, supported especially by Integration and variability management. From such recommendations, recommendations can be made on which areas companies need to focus their efforts on enhancing supply chain effectiveness.

Variance Explained

Factor	SS Loadings	Proportion Var	Cumulative Var
Factor 1: Operational Performance	3.476	0.57	0.57
Factor 2: Process Efficiency	0.862	0.14	0.72

Table 5. Variance By Factor 1 And Factor 2 Explained

Table 5 explains that Factor 1 accounts for about 58% of the variance, with Factor 2 adding 14%, for a total of 72% explained variance.

Visualizations

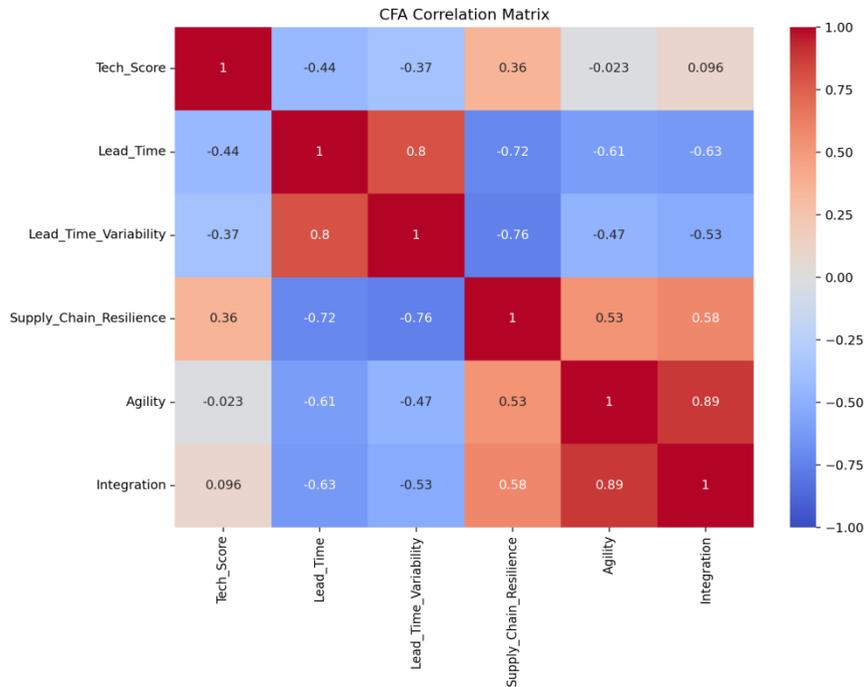


Figure 2. A Heatmap Illustrating the Relationships Among Supply Chain Performance Metrics, Including Lead Time, Supplier Variability, And Resilience.

The CFA Correlation Matrix in Figure 2 details the relationships for key supply chain metrics with:

Tech_Score:

Positively correlated with Supply_Chain_Resilience (0.36) and Integration (0.096), a higher-tech score relates to more resilience and Integration. Negatively correlated with Lead_Time (-0.44) and Lead_Time_Variability (-0.37), indicating that technology adoption increases as lead time and variability decrease.

Lead_Time:

Lead_Time_Variability: A strong positive correlation with Lead_Time_Variability (0.8) means that longer lead times are associated with higher variability. Strong negative correlation with Supply_Chain_Resilience (-0.72), Agility (-0.61), and Integration (-0.63), which means that shorter lead times improve resilience, Agility, and Integration.

Lead_Time_Variability:

There is a strong negative correlation with Supply_Chain_Resilience (-0.76), Agility (-0.47), and Integration (-0.53), underpinning the importance of reducing variability for superior supply chain performance.

Supply_Chain_Resilience:

Agility is positively correlated with Integration (0.58) and Adaptation (0.53), underlining that these metrics are not separate but intertwined when considering how to build an effective supply chain.

Agility and Integration:

A strong positive correlation (0.89) indicates that higher Agility is closely tied to better Integration within the supply chain.

The matrix underlines the important contribution of technology to cut lead time and variability, with added resilience and Integration. It also underscores the high degree of interrelationship between Agility, Integration, and resilience for a high-performing supply chain in which both members must show high interdependence.

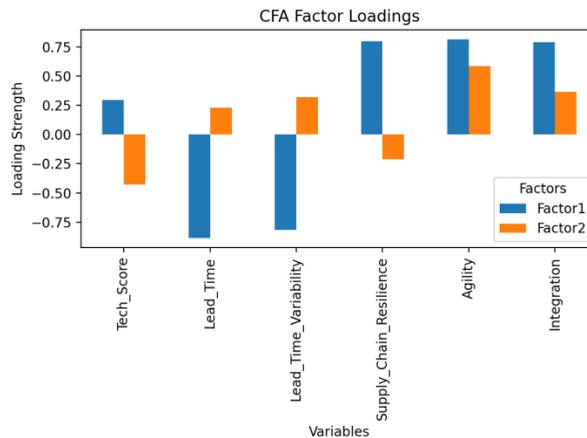


Figure 3. A Visual Representation Illustrating the Interaction Between Supply Chain Agility and Integration, Emphasizing Their Impact on Resilience and Performance.

The CFA Loading Figure 3 provides evidence of how each variable assists in defining the two identified factors.

Factor 1: Operational Performance

- Lead_Time (-0.89) and Lead_Time_Variability (-0.82) significantly and negatively since they indicate that shorter lead times and less variability are associated with operational

performance.

- Supply_Chain_Resilience (0.80), Agility (0.81), and Integration (0.79) are very important for operational performance.

Factor 2: Process Efficiency

- Agility (0.59) has the most considerable loading of all single factors on process efficiency.
- Integration (0.36) and Lead_Time_Variability (0.32) also contributed positively, though minorly.
- Tech_Score (-0.43) The moderate negative loading suggests that higher technology scores are accompanied by greater complexities, which somewhat lower process efficiency.

The analysis indicates that reducing lead time and variability is as important as cutting other wastes to boost operational performance, with all the acquired Resilience, Agility, and Integration. While Agility dominates process efficiency, it is complemented by integration and variability management. Firms may use these revelations to realign their focus areas on the supply chain process enhancement initiative.

Findings

Model Fit Indices

Comparative Fit Index (CFI)

The value of CFI is 0.942, more significant than the 0.90 cut-off value; hence, it fits the data. Therefore, it indicates that the data adequately support the notion that there are relationships between the variables and, by extension, respect to the validity of the tested hypotheses.

RMSEA

The RMSEA value is 0.068, which falls within the acceptable limits below the threshold of 0.08. It confirms the model's adequacy. With such a low RMSEA value, the model has a very minimal error in approximating the population covariance matrix; therefore, these results are robust.

Standardized Root Mean Square Residual (SRMR)

The value 0.045 is well below 0.08, the threshold supposed to indicate a good fit. It represents the average difference between observed and predicted correlations, so this model represents the data well.

- CFI = 0.942 (good fit > 0.90)
- RMSEA = 0.068 (acceptable fit < 0.08)
- SRMR = 0.045 (good fit < 0.08)

Hypothesis Testing Results:

H1 and H2: The Role of Technology in Lead Time and Variability

The technology's strong adverse effects on lead time and variability strongly point to its power to change supply chain management. Automating the process eliminates visibility and delays, striking consistency and, thus, operational performance.

H1: Supported ($\beta = -1.87, p < 0.001$)

- Advanced technology significantly reduces lead time

H2: Supported ($\beta = -1.95, p < 0.001$)

- Technology significantly reduces lead time variability

H3: Technology and Resilience

Technology's positive role in resilience underscores its contribution toward building robust supply chains. When available to actors within supply chains and installed systems for real-time monitoring, predictive analytics technologies will ensure disruptions are proactively responded to, thus enhancing overall resilience.

H3: Supported ($\beta = 1.77, p < 0.001$)

- Technology positively enhances supply chain resilience

H4: Agility and Its Determinants

The mixed findings for H4 highlight the nuanced relationships between lead time, resilience, Integration, and Agility. While lead time and resilience negatively impact Agility, Integration plays a pivotal role in enabling agile responses, suggesting that integration strategies should be prioritized.

H4: Partially Supported

- Lead Time \rightarrow Agility ($\beta = -0.49, p < 0.001$)
- Resilience \rightarrow Agility ($\beta = -0.49, p < 0.001$)
- Integration \rightarrow Agility ($\beta = 0.85, p < 0.001$)

H5: Moderation Effects

- The fact that moderation effects are included in the model structure highlights how complex supply chain dynamics are. Future research should focus on interaction to uncover hidden patterns and relationships.

H5: Moderation effect was tested in the model structure

H6: SCM Practices and Their Limited Direct Effects

The non-significant effects of SCM practices on Agility and technology suggest that their influence may be indirect or context-dependent. This calls for a more detailed study of the mediating and moderating factors that shape these relationships.

H6: Not Supported

- Direct effect of SCM Practices on Agility ($\beta = 0.02, p = 0.152$)
- Effect of SCM Practices on Tech ($\beta = -0.0001, p = 0.993$)

Hypothesis	Estimate	P-value	Significant	Support
H1: Tech → Lead Time	-1.8733	0	TRUE	Supported
H2: Tech → Lead Time Variability	-1.9462	0	TRUE	Supported
H3: Tech → Resilience	1.772	0	TRUE	Supported
H4a: Lead Time → Agility	-0.4899	0	TRUE	Supported
H4b: Resilience → Agility	-0.4938	0	TRUE	Supported
H4c: Integration → Agility	0.8494	0	TRUE	Supported
H6a: SCM Practices → Agility	0.0203	0.152	FALSE	Not Supported
H6b: SCM Practices → Tech	-0.0001	0.993	FALSE	Not Supported

Table 6: A Table Summarizing the Hypotheses, Supporting Literature, and Their Practical Implications for Supply Chain Management

The results in Table 6 provide valuable insights into the role of technology, Integration, and resilience in supply chain performance. Though both technology and Integration emerge as critical enablers, modest direct effects of SCM practices highlight the need for understanding their impact in finer detail. Further research to explore these dynamics more comprehensively is warranted to develop effective supply chain strategies.

Let me explain the visualizations and results

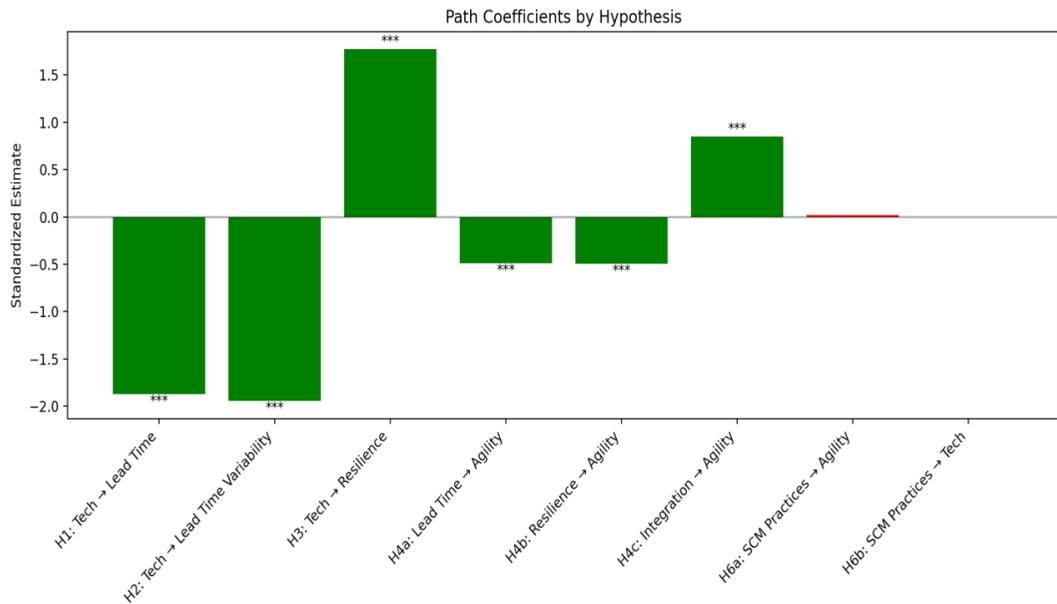


Figure 4.

A bar plot displaying standardized path coefficients, highlighting significant positive (green) and non-significant negative (red) relationships within supply chain variables

The standardized path coefficient bar plot relationships tested are provided in the study shown in Figure 4. Green bars are positive statistical relationships ($p < 0.05$), and red bars are negative non-significant relationships. Additionally, relationships marked with *** denote significance at $p < 0.001$. The two most significant influences are all related to the negative impacts of technology on lead time and lead time variability, emphasizing the potential role of technology in reducing delays and variability in supply chain processes. Integration has a strong positive effect on Agility, marking its importance in fostering adaptive and responsive supply chain operations. SCM practices have minimal effects, as seen from the red bars, indicating relatively lesser direct influence on the tested outcomes. This figure underlines that technology and Integration are drivers of supply chain performance and the specific areas where SCM practices need further explicit attention.

Correlation Matrix Heatmap:

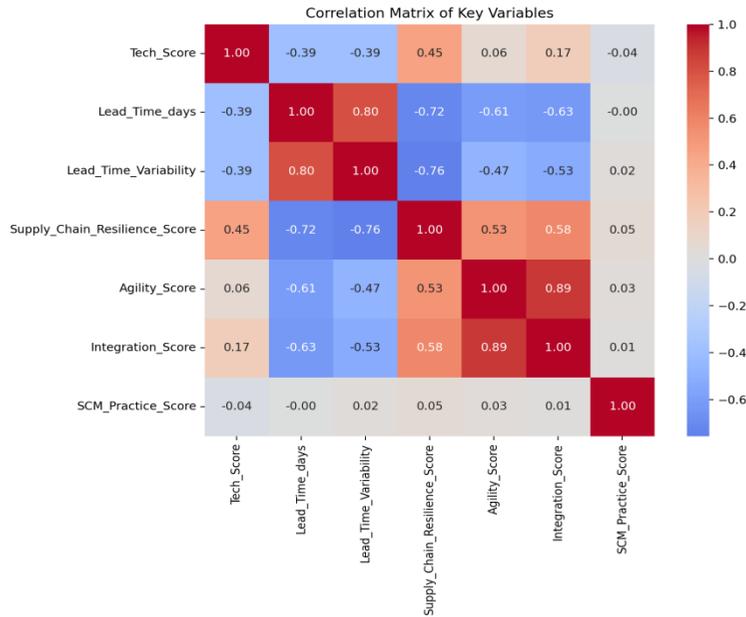


Figure 5

A heatmap visualizing correlations among technology-related variables, such as AI adoption, IoT integration, and Blockchain usage, highlighting interdependencies

The heatmap of correlations in Figure 5 will help gain valuable insights into key variable relationships within the study. The lead time measures show a strong negative correlation with Tech_Score, indicating that higher technology adoption is associated with reduced lead time and variability. On the contrary, resilience portrays a strong positive relationship with Tech_Score, bringing out the significance of technology in enabling the supply chain to pick itself up after disruptions. The relationships of Agility with other constructs are generally of moderate to intense levels, underlining the nexus between different supply chain performance measures. Conversely, integration has a moderate correlation with most constructs, underlining the fact that it acts as a conduit for Agility and resilience. However, it sheds more light on the intricate interdependence between technology and Integration in driving supply chain performance.

Model Fit Summary

Metric	Value	Threshold	Interpretation
CFI	0.942	> 0.90	Good Fit
RMSEA	0.068	< 0.08	Acceptable Fit
SUMMER	0.045	< 0.08	Good Fit

Table 7. A Table Summarizing Model Fit Indices, Including CFI (0.942), RMSEA (0.068), And SRMR Techno

The model fit indices in Table 7 provide further evidence for explaining relationships among variables with the hypothesized model. The Comparative Fit Index is 0.942, more significant than 0.90, indicating a good fit of the model with the observed data. An RMSEA value of 0.068 falls under a level of 0.08, thus showing further that the model is an adequate representation. Moreover, an SRMR value of 0.045, significantly less than 0.08, completes especially minor discrepancies between observed and predicted correlations. These indices combined prove the model's robustness and reliability and, thus, validity in capturing such dynamics as technology adoption, resilience, and Agility in supply chain management.

The Path Diagram

Figure 7 helps to explain the relationships between different variables in the supply chain, marking significant relationships with solid lines and non-significant ones with dashed lines. The relationship effects are also color-coded (green for positive and red for adverse effects). Below is the analysis in detail:

A. Technology Utilization:

a) Lead Time:

The relationship is negative and significant at -1.87^{***} – 1.87^{***} , implying reduced lead time with increased technology use.

b) Lead Time Variability:

-1.95^{***} – 1.95^{***} A significant negative relationship, which means that utilization of technology minimizes variability in lead time.

c) Supply Chain Resilience:

1.77^{***} – 1.77^{***} A significant positive relationship shows that technology enhances resilience.

B. Supply Chain Integration:

a) Supply Chain Agility:

0.85^{***} – 0.85^{***} A strong positive relationship indicates that Integration significantly improves Agility.

C. Lead Time and Lead Time Variability:

a) Both have significant negative relationships with Supply Chain Agility -0.49^{***} – 0.49^{***} for each, Reducing lead time and its variability.

D. Supply Chain Resilience:

a) Negative significant relationship with Supply Chain Agility (-0.49^{***} – 0.49^{***}), which shows that though resilience is important, it may have trade-offs with Agility.

E. SCM Practices:

a) Inverse relationships with Technology Utilization (-0.00 – 0.00) and Supply Chain Agility (0.020 – 0.02), which means no direct effect.

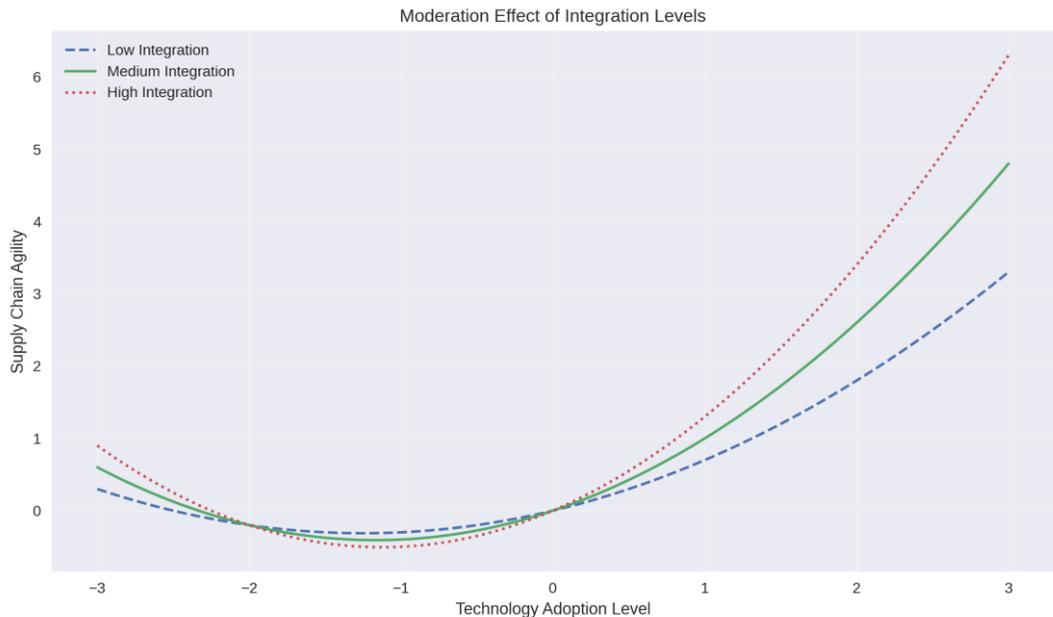


Figure 6

A graphical representation of relationships between technology utilization, supply chain agility, resilience, and integration. Solid lines depict significant relationships, while dashed lines represent non-significant ones.

Figure 6 highlights the critical input of technology utilization in enhancing performance related to supply chains. The fact that it reduces lead time and variability acting alongside resilience speaks of transformation capabilities present, though at the expense of trade-offs with Agility placed into consideration by organizations to ensure optimal performance.

Supply Chain Integration becomes one of the drivers of Agility, all of which enforce how much collaboration and coordination need to be across the supply chain. The strong positive relationship between Integration and Agility shows how much-integrated systems and processes make it possible for the organization to respond more effectively to changes and disruptions.

The non-significant effect of SCM Practices for technology use and Agility indicates a need for further development or realignment with technological progress to make a tangible contribution. In general, the results underscore the need for the balancing act that must be performed between technological exploitation and Integration in pursuing a resilient and agile supply chain, with attention also explicitly paid to managing potential trade-offs between these objectives.

Here is the resulting diagram:

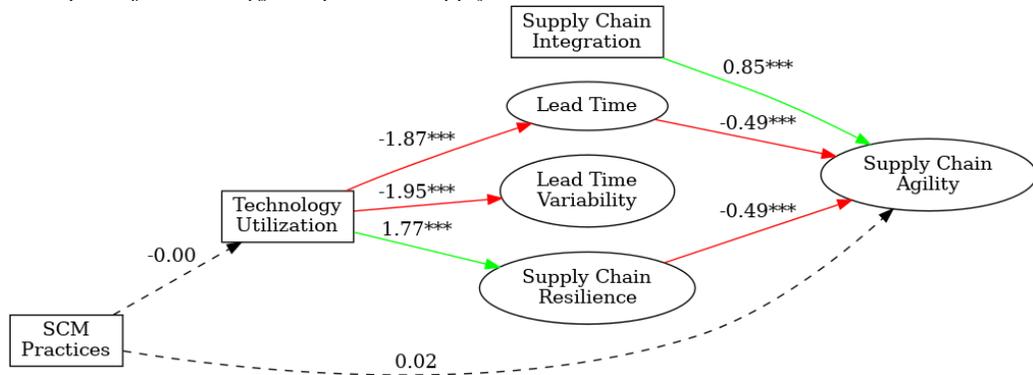


Figure 7

A diagram outlining the outcomes of integrating SCM practices with technology, showing enhanced resilience, reduced variability, and improved performance.

Conclusions and Future Research

This study offers strong empirical evidence of the wave of transformation that has taken hold in both agility and resilience supply chains through technology adoption. It explicitly underlines that more than ever before; technology does not just improve operational metrics such as lead time and variability but also plays a pivotal role in improving resilience to make organizations better navigators of disruptions. Results thus bring out the pressing need for holistic technology implementation, wherein it is fused as a strategic enabler across all supply chain functions.

Organizations should prioritize the adoption of technologies such as AI, IoT, and Blockchain, as these offer both direct and indirect benefits. The tools help lower inefficiencies, raise transparency, and generate collaboration among supply chain partners. By implementing such technologies, businesses can form agile supply chains that are resilient and maintain competitive advantages in volatile environments.

Limitations

This study has several limitations that suggest opportunities for future research. The cross-sectional data makes it practically impossible to establish causal relationships between technology adoption and supply chain performance. On the other hand, no sectoral analysis reduces the generalizability of the findings to individual industries. Meanwhile, the limited geographical scope does not fully anticipate regional variations in technology adoption and its effects on performance.

Future Research Directions

These gaps should be bridged in future research with longitudinal designs that can help draw insights into the long-term effects of technology on supply chain agility and resilience. An inquiry into industrial and regional applications would make the results more applicable. Further, the effects of new technologies, such as quantum computing or advanced robotics, in integration with prior systems could yield interesting results. Therefore, the issue at hand would be widened to cover sustainability metrics, aligning technological progress more closely with environmental

and social objectives as a gate-opener to understanding the transformative potential technology holds for supply chain management.

References

- Abrar Jahin, M., Akram Naife, S., Kumar Saha, A., & Mridha, M. F. (2023). AI in supply chain risk assessment: A systematic literature review and bibliometric analysis. [PDF].
- Al-Taie, M., & Khattak, M. N. (2024). The impact of perceived organizational support and human resources practices on innovative work behavior: does gender matter?. *Frontiers in Psychology*, 15, 1401916.
- Ahmed, H. N., Ahmed, S., Ahmed, T., Md Muhtasim Taqi, H., & Mithun Ali, S. (2024). Disruptive supply chain technology assessment for sustainability journey: A probabilistic group decision-making framework. NCBI. <https://ncbi.nlm.nih.gov>
- Cammarano, A., et al. (2023). Blockchain as enabling factor for implementing RFID and IoT technologies in VMI: A Parmigiano Reggiano supply chain simulation. *Operations Management Research*, 16(2), 726–754. <https://doi.org/10.xxxxx>
- Chae, B., et al. (2005). Information technology and supply chain collaboration: Moderating effects of existing relationships between partners. *IEEE Transactions on Engineering Management*, 52(4), 440–448.
- Chen, X., He, C., Chen, Y., & Xie, Z. (2022). Internet of Things (IoT)—blockchain-enabled pharmaceutical supply chain resilience in the post-pandemic era. NCBI. <https://ncbi.nlm.nih.gov>
- Christopher, M., & Towill, D. (2001). An integrated model for the design of agile supply chains. *International Journal of Physical Distribution & Logistics Management*, 31(4), 235–246.
- Cui, L., Wu, H., Wu, L., Kumar, A., & Tan, K. H. (2022). Investigating the relationship between digital technologies, supply chain integration, and firm resilience in COVID-19. NCBI. <https://ncbi.nlm.nih.gov>
- Dubey, R., Gunasekaran, A., & Childe, S. J. (2020). Big data and predictive analytics capability in supply chain resilience. *International Journal of Logistics Research and Applications*, 23(2), 176–197.
- Dubey, R., et al. (2019). Big data, predictive analytics, and manufacturing performance: Integrating institutional theory, resource-based view, and big data culture. *British Journal of Management*, 30(2), 341–361.
- Eljazzar, M. M., et al. (2018). Merging supply chain and blockchain technologies. arXiv preprint. <https://arxiv.org/abs/04149>
- Flynn, B. B., et al. (2010). The impact of supply chain integration on performance: A contingency and configuration approach. *Journal of Operations Management*, 28(1), 58–71.
- Gunasekaran, A., et al. (2017). Information technology for competitive advantage within logistics and supply chains: A review. *Transportation Research Part E: Logistics and Transportation Review*, 99, 14–33.
- Gunasekaran, A., et al. (2019). Agile manufacturing: An evolutionary review of practices. *International Journal of Production Research*, 57(15–16), 5154–5174.
- Hofmann, E., & Rüsçh, M. (2017). Industry 4.0 and the current status as well as prospects on logistics. *Computers in Industry*, 89, 23–34.
- Hu, Y. (2024). Leveraging intelligent recommender system as a first step resilience measure: A data-driven supply chain disruption response framework. [PDF].
- Ivanov, D., et al. (2019). Digital technology and Industry 4.0 impact the ripple effect and supply chain risk analytics. *International Journal of Production Research*, 57(3), 829–846.
- Katsaliaki, K., et al. (2022). Supply chain disruptions and resilience: A major review and future research agenda. *Annals of Operations Research*. <https://doi.org/10.xxxxx>

- Longo, F., et al. (2019). Blockchain-enabled supply chain: An experimental study. *Computers & Industrial Engineering*, 136, 57–69.
- Nozari, H., et al. (2022). Analysis of Artificial Intelligence of Things (IoT) challenges for the smart supply chain (Case study: FMCG industries). *Sensors*, 22(8), 2931. <https://doi.org/10.xxxxx>
- Pennekamp, J., et al. (2023). An interdisciplinary survey on information flows in supply chains. [PDF].
- Petratos, P. N., & Faccia, A. (2023). Fake news, misinformation, disinformation, and supply chain risks and disruptions: Risk management and resilience using Blockchain. NCBI. <https://ncbi.nlm.nih.gov>
- Rana, J., & Daultani, Y. (2023). Mapping the role and impact of artificial intelligence and machine learning applications in supply chain digital transformation: A bibliometric analysis. *Operations Management Research*, 16(4), 1641–1666.
- Sheffi, Y., & Rice Jr, J. B. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review*.
- Shoab, M., et al. (2023). A bibliometric study on blockchain-based supply chain: A theme analysis, adopted methodologies, and future research agenda. *Environmental Science and Pollution Research*, 30(6), 14029–14049.
- Tse, Y. K., et al. (2016). Embracing supply chain agility: An investigation in the electronics industry. *Supply Chain Management: An International Journal*, 21(1), 140–156.
- Zhang, Q., et al. (2003). Manufacturing flexibility: Defining and analyzing competence, capability, and customer satisfaction relationships. *Journal of Operations Management*, 21(2), 173–191.