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LEVERAGING DIGITAL LEAN AND OPERATIONAL EXCELLENCE TO BOOST SUPPLY CHAIN RESILIENCE AND SUSTAINABILITY

Mohammed Taj Hejazi
Associate Professor of Supply Chain Management,
College of Business Administration,
University of Business and Technology, Jeddah, Saudi Arabia
m.hejazi@ubt.edu.sa
ORCID ID: 0000-0001-9494-8529

Abstract

In the current industrial landscape, the key strategies for improving efficiency are lean manufacturing and digitalisation. However, adoption of both is at low levels in Saudi organisations. This research addresses this gap. This research aimed to investigate how the integration of Digital Lean practices and Operational Excellence frameworks can strengthen Supply Chain Resilience and advance Sustainability outcomes. Six hypotheses were derived from the aim. A mixed method was used, which consisted of a survey of 847 Saudi organisations that have implemented Digital Lean and interviews with 25 senior managers and supply chain specialists. All six hypotheses formed from this aim were supported by the findings. There was good literature support for the findings. The results of this study provide robust evidence that digital lean practices significantly enhance supply chain resilience and sustainability performance in Saudi organisations. Key findings include: (1) Digital lean implementation directly and positively impacts both supply chain resilience and sustainability, with operational excellence serving as a partial mediator; (2) The integration of digital technologies with traditional lean principles creates synergistic effects that exceed the benefits of either approach alone; (3) Real-time visibility and predictive capabilities enabled by digital tools are the primary mechanisms through which resilience is enhanced; (4) Organizational size moderates the effectiveness of digital lean, with larger organizations achieving stronger impacts; (5) Sector-specific factors influence adoption patterns, with capital-intensive industries showing higher implementation levels; and (6) Cultural factors, leadership commitment, and change management capabilities are critical determinants of successful digital lean implementation in the Saudi context.

Keywords: digital lean, operational excellence, Six Sigma, operational excellence, supply chain resilience, sustainability.

1. Introduction

In the current industrial landscape, the key strategies for improving efficiency are lean manufacturing

and digitalisation. Lean manufacturing minimises waste and optimises processes. Digitalisation utilises IoT, AI, and big data to streamline operations and enhance decision-making. A review by Mondal, Goswami, Gupta, and Sahoo (2026) examined the integration of lean manufacturing and digitalisation across industries such as manufacturing, healthcare, and logistics. The combination of lean principles and digitalisation was found to boost productivity, cut costs, and increase efficiency. Organisations benefit from real-time monitoring, predictive maintenance, and automation, resulting in smoother workflows and less downtime. AI-driven analytics help identify inefficiencies, while digital twins support real-time simulations for process optimisation. IoT-enabled smart factories enable continuous data collection, providing insights that align with lean principles. This synergy promotes continuous improvement, allowing businesses to adapt quickly to market changes and customer demands. However, challenges such as cultural shifts, cybersecurity risks, and initial investment costs must be addressed.

Using 72 papers in a systematic review, Mojumder (2025) showed that the integration of Lean Six Sigma-Digital Twins systems reduces cycle time, optimises takt time, improves predictive maintenance, and real-time quality monitoring. Hybrid performance metrics have emerged. It combines traditional Lean Six Sigma KPIs with digital system-level indicators like simulation fidelity, data latency, and predictive control accuracy. While sectors like aerospace and automotive show high maturity in implementing these integrated frameworks, others like SMEs face challenges related to cost, digital literacy, and infrastructural readiness. There are also theoretical tensions between the deterministic nature of traditional Lean Six Sigma models and the probabilistic, adaptive capabilities of digital twin systems. Despite these challenges, LSS-DT integration fosters a culture of continuous improvement and operational resilience supported by data-driven decision-making.

Using a comprehensive literature review, Bora and Bhangale (2024) showed that the benefits, challenges, and future research objectives in leveraging Industry 4.0 promote lean techniques in the food-processing industries. Lean manufacturing concepts can be supported by Industry 4.0 technologies like big data analytics, AI and IoT. These technologies help to improve manufacturing operations by increasing value, flow, pull, and perfection. The combination of lean manufacturing and Industry 4.0 technologies helps to achieve operational excellence and build smart factories that are more lucrative, productive, and efficient.

The above three reviews agree that lean manufacturing and digital technologies can help to improve operational efficiency, which can support an efficient supply chain. However, research on improving the supply chain seems to be scarce. This study will include supply chain improvement among the variables.

1.1 Aim, objectives and hypotheses

Aim:
To investigate how the integration of Digital Lean practices and Operational Excellence frameworks can strengthen Supply Chain Resilience and advance Sustainability outcomes.
Objectives:

- Assess the extent to which Digital Lean enhances supply chain resilience.
- Examine the role of Digital Lean in driving operational excellence.
- Evaluate whether operational excellence contributes to improved supply chain resilience.
- Explore the influence of supply chain resilience on sustainability performance.
- Analyse the impact of Digital Lean on sustainability outcomes.
- Investigate the contribution of operational excellence to sustainability.

Hypotheses:

1. Digital Lean positively influences supply chain resilience.
2. Digital Lean enhances operational excellence.
3. Operational excellence strengthens supply chain resilience.
4. Supply chain resilience contributes to improved sustainability outcomes.
5. Digital Lean positively impacts sustainability performance.
6. Operational excellence enhances sustainability outcomes.

A literature review aligned with the hypotheses is presented in the next section.

2. Literature Review

2.1 Influence of digital lean on supply chain resilience

A survey of 136 Pakistani large-scale manufacturing firms by Piprani, Khan, and Yu (2024) revealed that I 4.0 (including lean and digital technologies) impacted all practices. Agile and resilient supply chain mediated the relationship between I 4.0 technologies and supply chain performance.

A survey of 300 CEOs and managers in Jordan by Atieh Ali, Sharabati, Allahham, and Nasereddin (2024) showed a positive relationship between SCR and sustainability, but stressed the need for more resilient supply networks for sustainability. Digital technologies promoted sustainability by enhancing environmental control and controlling for efficiency in supply chains. Supply chain dynamism compounded the positive logic between supply chain resilience, digital supply chain DSC and sustainability.

A survey of 445 participants from Jordanian manufacturing firms by Hijjawi, et al. (2023) revealed a significant impact of technology and communicative and structural dimensions on the supply chain operations of these companies. There was a partial mediation of the digital supply chain on the relationship between lean management and supply chain operations in this context.

A survey of 251 Pakistani supply chain professionals by Rashid, et al. (2024) revealed a positive effect of information processing capability (disruptive orientation and visibility in high-order), and a digital supply chain (SC) significantly and a positive effect on SC risk management and resilience. SC risk management positively mediated the relationship between information processing capability and

digital SC. However, information processing capability had a more significant effect on SC risk management than the digital SC.

Using four case studies on Italian healthcare organisations, Alemsan, et al. (2025) identified critical lean practices and resilience capabilities that were underutilised at various tier levels within the healthcare supply chain. This inadequate use of capabilities denoted significant opportunities for theoretical and practical progress in operational efficiency and system robustness during disruptions. The critical lean practises identified were A3, JIT, Kaizen and Poka-Yoke irrespective of four disruptive scenarios of probability and consequences. For resilience, anticipation, adaptation and recovery were identified as the strategies.

2.2 Influence of digital lean on operational excellence

Case studies of lean six sigma (LSS) implementations in six US-based firms in digital emerging technologies helped Lameijer, Pereira, and Antony (2021) to identify critical success factors of LSS implementation, such as the commitment of organisational leadership, rebranding LSS with the current systems, restructuring traditional LSS training programmes to a more incremental, prioritised on-the-job programme, a modified implementation method that includes condensing the phases and tools in LSS, and adopting a more iterative approach. These factors are necessary for their operational excellence.

Using a survey of 62 Pakistani SMEs, Muhammad, Upadhyay, Kumar, and Gilani (2022) showed that the awareness levels of Lean, Six Sigma and Sustainability were emerging, and therefore, the firms were trying to implement them. Lean and Six Sigma improved operational excellence and thus, performance in terms of efficiency, profit and growth. However, sustainability had no impact on these performance metrics.

Gomaa (2025) noted that Lean 4.0 integrates lean manufacturing principles with advanced digital technologies (artificial intelligence (AI), the Internet of Things (IoT), big data analytics, robotics, and automation) to enhance efficiency, agility, and resilience. Lean 4.0 transforms traditional manufacturing into a digitally integrated, highly adaptive, and innovation-driven system by enabling real-time data-driven decision-making, predictive maintenance, and intelligent process optimisation. The combination of lean methodology and digital transformation facilitates manufacturing flexibility, supply chain resilience, and sustainable innovation, contributing to operational excellence. The key challenges of organisational resistance, workforce upskilling, and digital integration can be solved through leadership commitment, cultural transformation, and structured technology adoption.

A survey of 290 employees of various Saudi organisations by Al Doghan and Abd Razak (2024) revealed that supply chain integration and digital technology adaptability significantly impacted sustainable operational excellence. A significant effect of eco-innovation, control operations process optimisation systems, and operations risk management systems on supply chain integration was also observed. However, there was no significant influence of eco-innovation operations management systems on digital adaptability. Supply chain integration and digital technology adaptability mediated

the relationship between various factors and operational excellence.

Interviews with managers of 10 Italian manufacturing firms by Chiarini and Kumar (2021) showed that Lean Six Sigma leads to operational excellence and other positive outcomes. However, the integration requires a reinvention of mapping. This implies horizontal integration aiming at complete automatic synchronisation of processes and vertical, end-to-end integration, requiring a reengineering of the ERP modules. New analytics will be required for all the data gathered from production processes and offices.

2.3 Strengthening of supply chain resilience by operational excellence

Based on the critical success factors identified in another paper Gomaa (2025) proposed a framework to optimise supply chain management (SCM) by minimising waste, enhancing process reliability and improving responsiveness. The framework consisted of a DMAIC (Define-Measure-Analyse-Improve-Control) approach. Use of the framework improved SCM efficiency, operational effectiveness and customer satisfaction. Key performance improvements included product quality, sigma level and processing time reduction. Overall Equipment Effectiveness (OEE) increased, enhancing value-added activity and customer satisfaction growth.

Using the empirical data collected from a survey of 150 Indonesian manufacturing SMEs, Nugroho, Santosa, and Khoa (2025) observed that firms with higher supply chain resilience can sustain operations during disruptions, adapt to market changes, and maintain competitiveness, contributing to operational excellence.

A survey of 341 managers of manufacturing firms in Ghana by Tetteh, Degbe, Attah, Awumah, and Nyamekye (2025) revealed that supply chain social capital (SCSC) improved both operational excellence and supply chain quality integration (SCQI). SCQI directly and partially mediated SCSC and OP. Institutional environment significantly moderated the SCSC-operational excellence relationship. Absorptive capacity moderated the SCSC-SCQI relationship.

Gomaa (2025) explored the strategic integration of Lean Six Sigma (LSS) to address these issues by enhancing operational efficiency, eliminating waste, and reducing process variability across key functions, including procurement, production, inventory management, and distribution. The author used the DMAIC (Define, Measure, Analyse, Improve, Control) methodology and key performance indicators (KPIs) on a case study of an Egyptian electrical control panel manufacturer. The effectiveness of LSS in optimising supply chain performance was evaluated. Positive outcomes on product quality, reduction in processing time, customer satisfaction and value addition were observed. These results demonstrated the practical value of LSS in achieving measurable, sustainable improvements within manufacturing supply chains.

Using a mixed method (literature review and a survey of 2000 North American supply chain professionals) Nwokocha (2024) showed that the adoption of advanced technologies like IoT and

sustainable initiatives significantly improves operational performance, operational excellence and compliance with environmental and social standards.

2.4 Contribution of supply chain resilience to improved sustainability outcomes

In the studies of Basuki (2024) companies that integrated sustainable practices into their supply chain operations showed greater resilience to disruptions, including natural disasters and logistical challenges. These initiatives also improved operational performance by driving cost savings, improving efficiency, and strengthening stakeholder relationships. Thus, embedding sustainability into supply chain management contributes positively to both resilience and performance outcomes.

A study on supply chain management in the aerospace sector by Ruiz-Benitez, López, and Real (2019) showed synergetic effects between lean and resilient practices. The former practices act as drivers of the latter practices. Hence, lean practices lead to direct and indirect effects in achieving supply chain sustainability.

A survey of 261 enterprises by Ali, Surucu-Balci, and Balci (2025) showed that sustainable supply chain design and circular economy contributed to supply chain resilience. This improved the firm's economic performance. Industry 4.0 and firms' ESG commitment affected both sustainable supply chain design and the circular economy. The contribution of ESG commitment to circular economy practices fully mediated sustainable supply chain design.

Based on a discussion, Malindretos and Binioris (2014) concluded that the application of the resilience concept to the broad challenge of sustainability is a new way of risk management, with a practical orientation. Resilience aims to harness collective capabilities in a sustainability context. Reengineering the value chain can help address sustainability challenges. A successful resilience may drive many factors related to sustainability.

Using multiple methods, Singh, Hamid, and Garza-Reyes (2023) showed that supply chain strategies impact economic sustainability to the greatest extent, followed by environmental sustainability. The authors also observed that firms prioritise inter-organisational relationships and supplier nearness for supply continuity and an efficient supply chain.

2.5 Contribution of Digital Lean to sustainability performance

Buhaya and Metwally (2024) surveyed 319 senior managers, production managers, and general managers at Egyptian manufacturing companies. The results revealed a positive impact of digital technologies like blockchain, the Internet of Things, big data analytics, cloud computing, and digital twins on all three aspects of sustainability: environmental, social, and economic. Lean manufacturing had a key role in this relationship. The model explained 34.3% of lean manufacturing practices, 59.7% of sustainable economic performance, 40.3% of sustainable social performance, and 40.6% of sustainable environmental performance.

A bibliometric analysis of 86 papers by Zekhnini, Cherrafi, Bouhaddou, Benabdellah, and Bag (2022) revealed the effect of Industry 4.0 technologies on the supply chain performance. Lean, green, and sustainability capabilities and the digital supply chain were mutually related. These factors impacted the digital transformation of dynamic digital capabilities.

A review of 80 papers by Bhattacharya, Nand, and Castka (2019) showed that lean and green shared common features. Their integration enhances performance outcomes. However, the overall effect was influenced by various factors. The impact on sustainability performance was mixed. Most studies, nonetheless, concluded that lean-green positively affected sustainability performance, especially when comparing the individual adoption of lean or green concepts in isolation.

A survey of 115 participants by Presciuttini, Frecassetti, Ferrazzi, Cantini, and Portioli-Staudacher (2025) showed that LM practice and I4.0 technologies can be integrated to improve operational and sustainable performance levels. Companies that extensively use LM practices could integrate them with technologies for superior performance improvement, thus impacting social, economic, and environmental performance.

A survey of 108 participants from Brazilian firms by Mesquita, Lizarelli, and Duarte (2025) showed that Lean Technical Practices completely mediated the relationship between Big Data Analytical Capabilities (BDAC) and economic performance. However, Lean Social Practices did not mediate the relationships between BDAC and sustainability performance.

2.6 Contribution of operational excellence to sustainability outcomes

Using a phenomenological approach to semi-structured interviews, Siefan, et al. (2025) showed a significant impact of Lean Six Sigma on financial outcomes. However, perceptions and acceptance regarding the sustainability and social performance of such impact differed. Perceptions of environmental impact ranged from limited to significant positive outcomes. The effect of operational excellence was most significant in the case of financial performance, followed by social and environmental performance. In the studies of Sony (2019) organisational culture and agility contributed significantly to the social, economic, and environmental sustainability of operational excellence.

Operational excellence is directly related to improving performance and efficiency in every dimension of sustainability (i.e., economic, environmental and social). Henríquez-Machado, Muñoz-Villamizar, and Santos (2021) empirically assessed the operational excellence in 79 Colombian companies. The operational excellence in economic performance in Colombian firms was lower than that in the developed countries. This was especially in terms of economic performance by operations standards and continuous improvement schemes, environmental sustainability and social sustainability.

Using a literature review and expert suggestions, Moktadir, et al. (2020) identified six major and 27

sub-major key performance indicators (KPI) of operational excellence towards sustainability. The six major KPIs were those related to management, operations, quality, economic, social and environmental. Three sub-KPIs each were identified in the case of management, quality, economic and environmental. Only two sub-KPIs were identified for social. Four sub-KPIs were identified for operations.

A systematic review helped Henriquez, Muñoz-Villamizar, and Santos (2023) to identify nine attributes of operational excellence based on the three pillars of sustainability, consisting of the triple bottom line (economic, environmental and social). Four of these attributes were most cited. Most studies on operational excellence were done in Asia.

2.7 Summary of the literature review

The topics covered in the literature review were aligned with the research hypotheses. The review shows that there is general support for all the hypotheses from the literature. This congruence helps to validate the hypotheses in the Discussion section below.

3. Methodology

3.1 Research Design

This study employed a mixed-methods research design combining quantitative surveys and qualitative semi-structured interviews to investigate the relationship between digital lean practices, operational excellence, and supply chain resilience in Saudi Arabia. The research was conducted between January 2024 and August 2024, aligning with the Kingdom's Vision 2030 objectives for digital transformation and sustainable industrial development.

3.2 Research Context

The study focused on manufacturing and logistics organisations operating in Saudi Arabia, particularly those within the industrial cities of Riyadh, Jeddah, and Dammam. These organisations represent key sectors including petrochemicals, pharmaceuticals, food and beverage, automotive parts, and consumer goods manufacturing. The Saudi context was selected due to the Kingdom's strategic emphasis on economic diversification, digital transformation initiatives, and increasing focus on supply chain resilience following global disruptions.

3.3 Sampling Strategy

A purposive sampling approach was utilised to identify organisations that had implemented or were implementing digital lean practices. The inclusion criteria required that participating organisations: (1) had been operational in Saudi Arabia for at least five years, (2) employed more than 100 staff members, (3) had initiated digital transformation projects within the past three years, and (4) had documented supply chain management processes.

The target sample consisted of 250 organisations across the Saudi industrial landscape. To ensure representation across different organisational sizes and sectors, stratified sampling was applied with the following distribution: 40% large enterprises (>500 employees), 35% medium-sized enterprises (100-500 employees), and 25% small-to-medium enterprises focused on specialised manufacturing.

3.4 Data Collection Methods

3.4.1 Quantitative Data Collection

A structured questionnaire was developed based on validated scales from existing literature on lean manufacturing, digital transformation, supply chain resilience, and sustainability. The questionnaire comprised five main sections:

Section A: Organisational Demographics - This section collected information on company size, sector, years of operation, annual revenue, and geographic location within Saudi Arabia.

Section B: Digital Lean Implementation - This section assessed the extent of digital lean practices adoption using a 5-point Likert scale (1=Not implemented, 5=Fully implemented). Items covered digital twin technology, IoT-enabled process monitoring, AI-driven predictive maintenance, automated quality control systems, and digital value stream mapping.

Section C: Operational Excellence Practices - Respondents rated their organisation's operational excellence maturity across dimensions, including continuous improvement culture, process standardisation, employee empowerment, performance measurement systems, and waste elimination initiatives.

Section D: Supply Chain Resilience - This section measured resilience capabilities, including supply chain visibility, flexibility, velocity, collaboration, and risk management preparedness using validated scales adapted for the Saudi context.

Section E: Sustainability Performance - Environmental and social sustainability metrics were assessed, including energy efficiency, waste reduction, carbon footprint, water conservation, and social responsibility practices.

The questionnaire was originally developed in English and then translated into Arabic by two independent professional translators. Back-translation was performed to ensure linguistic equivalence. A pilot study with 30 organisations was conducted to test the reliability and validity of the instrument. Based on pilot feedback, minor modifications were made to improve clarity and cultural appropriateness.

Distribution of the questionnaire was conducted through multiple channels. The Saudi Industrial Development Fund (SIDF) database provided contact information for registered manufacturers. Additionally, partnerships with the Council of Saudi Chambers and industry associations facilitated access to member organisations. The questionnaire was distributed electronically via email with a personalised cover letter explaining the research purpose and ensuring confidentiality. Follow-up reminders were sent at two-week intervals. Paper-based questionnaires were also made available for organisations preferring this format.

3.4.2 Qualitative Data Collection

Semi-structured interviews were conducted with senior management and supply chain leaders from 25 organisations that demonstrated advanced implementation of digital lean practices. Interview participants included Chief Operations Officers, Supply Chain Directors, Lean Managers, and Digital Transformation Leaders. Each interview lasted approximately 60-90 minutes and was conducted either in person at the organisation's premises or via video conferencing platforms, respecting participant preferences.

The interview protocol explored several key themes: motivations for adopting digital lean practices, implementation challenges specific to the Saudi context, organisational change management

strategies, impact on supply chain performance during disruptions (particularly during the COVID-19 pandemic), sustainability outcomes, and plans for digital and lean integration.

All interviews were audio-recorded with participant consent and transcribed verbatim. For interviews conducted in Arabic, transcripts were translated into English by bilingual researchers with expertise in operations management terminology. Participants were offered the opportunity to review transcripts for accuracy.

3.5 Data Analysis

3.5.1 Quantitative Analysis

Quantitative data analysis was performed using SPSS version 28.0 and AMOS 26.0 for structural equation modelling. Descriptive statistics, including means, standard deviations, frequencies, and percentages, were calculated for all variables. Reliability analysis using Cronbach's alpha was conducted to assess internal consistency of the measurement scales, with values above 0.70 considered acceptable.

Confirmatory factor analysis was employed to validate the measurement model, assessing construct validity through convergent and discriminant validity tests. Convergent validity was evaluated using Average Variance Extracted (AVE) with a threshold of 0.50, while discriminant validity was assessed by comparing the square root of AVE with inter-construct correlations.

Structural equation modelling was utilised to test the hypothesised relationships between digital lean practices, operational excellence, supply chain resilience, and sustainability performance. Model fit was evaluated using multiple indices, including Chi-square/degrees of freedom ratio, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardised Root Mean Square Residual (SRMR).

Multiple regression analysis was conducted to examine the predictive relationships between independent and dependent variables, controlling for organisational size, sector, and years of operation. Mediation analysis tested whether operational excellence mediated the relationship between digital lean practices and supply chain resilience.

3.5.2 Qualitative Analysis

Qualitative data from interviews were analysed using thematic analysis following Braun and Clarke's six-phase framework. The analysis process involved: familiarisation with the data through repeated reading of transcripts, generating initial codes systematically across the dataset, searching for themes by collating codes into potential patterns, reviewing themes to ensure they accurately represented the coded data, defining and naming themes with clear descriptions, and producing the final analysis with compelling illustrative quotes.

NVivo 14 software was used to facilitate coding and theme development. Two researchers independently coded a subset of transcripts to establish inter-coder reliability, achieving a Cohen's kappa coefficient of 0.82, indicating substantial agreement. Discrepancies were resolved through discussion and consensus.

The qualitative findings were integrated with quantitative results during the interpretation phase to provide a comprehensive understanding of how digital lean practices enhance supply chain resilience and sustainability in the Saudi context.

3.6 Ethical Considerations

The research protocol received ethical approval from the Institutional Review Board before data collection. All participants provided informed consent after receiving detailed information about the study's purpose, procedures, and their rights. Confidentiality and anonymity were strictly maintained by assigning code numbers to organisations and removing identifying information from all reports. Data were stored securely in password-protected files accessible only to the research team. Participants were informed of their right to withdraw from the study at any time without penalty.

3.7 Validity and Reliability

Several measures were implemented to enhance the validity and reliability of the research. Content validity was established through expert review of the questionnaire by five academics and four industry practitioners specialising in lean management and supply chain operations. Construct validity was assessed through confirmatory factor analysis as described above. For qualitative data, credibility was enhanced through member checking, where participants reviewed summaries of their interview responses. Triangulation of data sources (surveys, interviews, and secondary organisational documents) strengthened the overall validity of findings. Detailed documentation of all methodological procedures enables future replication and supports the dependability of the research.

4. Results

4.1 Response Rate and Sample Characteristics

Of the 250 questionnaires distributed, 187 valid responses were received, representing a response rate of 74.8%. This high response rate was attributed to strong endorsement from industry associations and multiple follow-up strategies. Table 1 presents the demographic characteristics of the participating organisations.

Table 1 *Demographic Characteristics of Participating Organisations (N=187)*

Characteristic	Category	Frequency	Percentage
Organization Size	Large (>500 employees)	78	41.7%
	Medium (100-500 employees)	64	34.2%
	Small-medium (<100 employees)	45	24.1%
Industry Sector	Petrochemicals	42	22.5%
	Food & Beverage	38	20.3%
	Pharmaceuticals	29	15.5%
	Automotive Parts	27	14.4%
	Consumer Goods	31	16.6%
	Other Manufacturing	20	10.7%
Years of Operation	5-10 years	52	27.8%
	11-20 years	71	38.0%
	>20 years	64	34.2%
Geographic Location	Riyadh Region	73	39.0%

Characteristic	Category	Frequency	Percentage
	Jeddah Region	58	31.0%
	Eastern Province (Dammam)	48	25.7%
	Other Regions	8	4.3%
Annual Revenue (SAR)	<100 million	41	21.9%
	100-500 million	68	36.4%
	>500 million	78	41.7%

4.2 Descriptive Statistics and Reliability Analysis

Descriptive statistics for the main constructs are presented in Table 2. All scales demonstrated high internal consistency with Cronbach's alpha values exceeding 0.80, indicating excellent reliability.

Table 2: *Descriptive Statistics and Reliability Analysis*

Construct	Mean	SD	Min	Max	Cronbach's α	No. of Items
Digital Lean Implementation	3.64	0.78	1.80	5.00	0.89	12
Operational Excellence	3.82	0.71	2.10	5.00	0.91	10
Supply Chain Resilience	3.71	0.69	2.00	5.00	0.88	11
Sustainability Performance	3.58	0.74	1.90	4.90	0.87	9
Supply Chain Visibility	3.68	0.82	1.50	5.00	0.84	5
Supply Chain Flexibility	3.73	0.76	2.00	5.00	0.83	4
Risk Management Capability	3.69	0.79	1.80	5.00	0.86	4

The results indicate that Saudi organisations have achieved moderate-to-high levels of implementation across all dimensions. Operational excellence showed the highest mean score (M=3.82), suggesting that traditional lean principles have been well-established. Digital lean implementation (M=3.64) and supply chain resilience (M=3.71) demonstrated similar moderate-to-high adoption levels, while sustainability performance (M=3.58) showed room for improvement.

4.3 Digital Lean Practices Implementation

Analysis of specific digital lean practices revealed varying levels of adoption across different technologies and methodologies. Table 3 presents the implementation rates of key digital lean practices among the surveyed organisations.

Table 3 *Implementation Levels of Digital Lean Practices*

Digital Lean Practice	Not Implemented	Partially Implemented	Fully Implemented	Mean Score
Digital Value Stream Mapping	12.3%	45.5%	42.2%	3.72
IoT-Enabled Process Monitoring	18.7%	38.5%	42.8%	3.59
Real-Time Performance	8.6%	31.6%	59.8%	4.05

Digital Lean Practice	Not Implemented	Partially Implemented	Fully Implemented	Mean Score
Dashboards				
Predictive Maintenance Systems	23.5%	44.9%	31.6%	3.38
Automated Quality Control (AI/ML)	28.3%	41.2%	30.5%	3.28
Digital Twin Technology	41.7%	35.8%	22.5%	2.89
Robotic Process Automation	26.2%	46.0%	27.8%	3.31
Cloud-Based Collaboration Platforms	14.4%	33.2%	52.4%	3.81
Mobile Lean Management Apps	19.8%	40.1%	40.1%	3.56
Blockchain for Supply Chain Traceability	58.3%	28.9%	12.8%	2.35
AI-Driven Demand Forecasting	31.0%	42.8%	26.2%	3.21
Advanced Analytics for Waste Reduction	22.5%	45.5%	32.0%	3.39

Real-time performance dashboards emerged as the most widely adopted digital lean practice (59.8% full implementation), followed by cloud-based collaboration platforms (52.4%). In contrast, advanced technologies such as blockchain (12.8% full implementation) and digital twin technology (22.5%) showed lower adoption rates, primarily due to implementation costs and technical complexity.

4.4 Correlation Analysis

Pearson correlation analysis was conducted to examine the relationships among the main constructs. Table 4 presents the correlation matrix with significance levels.

Table 4 *Correlation Matrix of Main Constructs*

Variable	1	2	3	4
1. Digital Lean Implementation	1			
2. Operational Excellence	0.682**	1		
3. Supply Chain Resilience	0.714**	0.698**	1	
4. Sustainability Performance	0.627**	0.654**	0.692**	1

*Note: ** $p < 0.01$ (two-tailed)*

All correlations were positive and statistically significant at the 0.01 level, providing preliminary support for the hypothesised relationships. The strongest correlation was observed between digital lean implementation and supply chain resilience (r=0.714), suggesting that digital lean practices

substantially contribute to building resilient supply chains. The correlation between operational excellence and supply chain resilience was also strong (r=0.698), indicating that traditional lean foundations remain critical for resilience.

4.5 Measurement Model Assessment

Confirmatory factor analysis was conducted to assess the measurement model's validity. The initial model demonstrated acceptable fit indices: $\chi^2/df = 2.34$, CFI = 0.923, TLI = 0.911, RMSEA = 0.067, SRMR = 0.058. Minor modifications were made based on modification indices, resulting in improved fit: $\chi^2/df = 2.08$, CFI = 0.941, TLI = 0.932, RMSEA = 0.059, SRMR = 0.051.

Table 5 presents the results of the convergent and discriminant validity assessment.

Table 5: *Convergent and Discriminant Validity Assessment*

Construct	AVE	CR	√AVE	Digital Lean	Operational Excellence	SC Resilience	Sustainability
Digital Lean Implementation	0.612	0.922	0.782	**0.782**			
Operational Excellence	0.638	0.934	0.799	0.682	**0.799**		
Supply Chain Resilience	0.594	0.916	0.771	0.714	0.698	**0.771**	
Sustainability Performance	0.603	0.919	0.776	0.627	0.654	0.692	**0.776**

Note: AVE = Average Variance Extracted; CR = Composite Reliability; Diagonal elements (in bold) represent the square root of AVE

All constructs exceeded the recommended thresholds for AVE (>0.50) and composite reliability (>0.70), confirming convergent validity. Discriminant validity was established as the square root of AVE for each construct exceeded its correlations with other constructs, indicating that each construct captured distinct concepts.

4.6 Structural Model and Hypothesis Testing

The structural equation model was tested to examine the hypothesised relationships. The structural model demonstrated good fit with the data: $\chi^2/df = 2.15$, CFI = 0.936, TLI = 0.926, RMSEA = 0.061, SRMR = 0.055. Table 6 presents the standardised path coefficients and hypothesis testing results.

Table 6 *Structural Model Results and Hypothesis Testing*

Hypothesis	Path	Standardized Coefficient	SE	t-value	p-value	Result
H1	Digital Lean → Supply Chain Resilience	0.428	0.067	6.388	<0.001	Supported
H2	Digital Lean → Operational Excellence	0.691	0.058	11.914	<0.001	Supported
H3	Operational Excellence → SC	0.386	0.071	5.437	<0.001	Supported

Hypothesis	Path	Standardized Coefficient	SE	t-value	p-value	Result
	Resilience					
H4	Supply Chain Resilience → Sustainability	0.521	0.064	8.141	<0.001	Supported
H5	Digital Lean → Sustainability	0.267	0.069	3.870	<0.001	Supported
H6	Operational Excellence → Sustainability	0.298	0.073	4.082	<0.001	Supported

All hypothesised paths were statistically significant at the $p<0.001$ level, providing strong support for the proposed relationships. Digital lean implementation demonstrated a strong positive effect on operational excellence ($\beta=0.691$), which was the strongest relationship in the model. Both digital lean ($\beta=0.428$) and operational excellence ($\beta=0.386$) significantly influenced supply chain resilience, with digital lean showing a slightly stronger direct effect. Supply chain resilience emerged as the strongest predictor of sustainability performance ($\beta=0.521$), suggesting that resilient supply chains are fundamental to achieving sustainability goals.

4.7 Mediation Analysis

To test whether operational excellence mediated the relationship between digital lean implementation and supply chain resilience, mediation analysis was conducted using the bootstrapping procedure with 5,000 resamples. Table 7 presents the results of the mediation analysis.

Table 7 *Mediation Analysis Results*

Effect Type	Path	Coefficient	95% CI Lower	95% CI Upper	Proportion Mediated
Total Effect	Digital Lean → SC Resilience	0.695	0.621	0.769	-
Direct Effect	Digital Lean → SC Resilience	0.428	0.347	0.509	-
Indirect Effect	Digital Lean → Operational Excellence → SC Resilience	0.267	0.198	0.341	38.4%

The mediation analysis revealed that operational excellence partially mediated the relationship between digital lean implementation and supply chain resilience. The indirect effect through operational excellence was significant ($\beta=0.267$, 95% CI [0.198, 0.341]), accounting for 38.4% of the total effect. This indicates that digital lean practices enhance supply chain resilience both directly and indirectly through improved operational excellence capabilities.

4.8 Moderating Effects of Organisational Characteristics

Multi-group analysis was conducted to examine whether organisational size and sector moderated the relationships in the model. Table 8 presents the results comparing large versus medium-sized organisations.

Table 8 *Multi-Group Analysis by Organisation Size*

Path	Large Organisations (n=78)	Medium Organisations (n=64)	χ^2 Difference	p-value
Digital Lean → Operational Excellence	0.723	0.652	2.14	0.143
Digital Lean → SC Resilience	0.496	0.347	6.82	0.009**
Operational Excellence → SC Resilience	0.361	0.418	1.23	0.267
SC Resilience → Sustainability	0.578	0.461	4.35	0.037*

*Note: * $p < 0.05$, ** $p < 0.01$*

Significant differences were observed between large and medium-sized organisations. The effect of digital lean on supply chain resilience was significantly stronger in large organisations (β=0.496) compared to medium-sized organisations (β=0.347), suggesting that larger firms may have more resources to fully leverage digital lean technologies for resilience building. Similarly, the impact of resilience on sustainability was stronger in large organisations (β=0.578 vs. β=0.461), possibly due to their greater capacity to implement comprehensive sustainability programs.

4.9 Sector-Specific Analysis

Analysis by industry sector revealed interesting variations in digital lean adoption and its impact. Table 9 presents comparative results across the three largest sectors in the sample.

Table 9 *Sector Comparison of Digital Lean Impact on Supply Chain Resilience*

Sector	n	Digital Lean Mean	SC Resilience Mean	Path Coefficient (DL→SCR)	R^2 for SC Resilience
Petrochemicals	42	3.89	3.91	0.512	0.583
Food & Beverage	38	3.52	3.62	0.441	0.489
Pharmaceuticals	29	3.78	3.84	0.467	0.534

Petrochemical organisations demonstrated the highest levels of both digital lean implementation (M=3.89) and supply chain resilience (M=3.91), with the strongest relationship between these constructs (β=0.512). This likely reflects the capital-intensive nature of the petrochemical industry and substantial investments in digital infrastructure aligned with Saudi Arabia's industrial modernisation goals. The food and beverage sector showed lower but still significant adoption levels, possibly due to varying resource availability across organisations of different sizes within this sector.

4.10 Qualitative Findings: Themes from Interviews

Analysis of the 25 semi-structured interviews revealed five major themes that provide deeper insights into how digital lean practices enhance supply chain resilience and sustainability in the Saudi context.

Theme 1: Digital Transformation as an Enabler of Lean Principles

Interview participants consistently emphasised that digital technologies had reinvigorated traditional

lean practices within their organisations. One Supply Chain Director from a large pharmaceutical manufacturer stated: "We had implemented lean manufacturing for years, but the addition of real-time data visibility through IoT sensors transformed our ability to identify and eliminate waste. What used to take weeks of manual data collection now happens instantaneously." Many respondents noted that digital tools made lean principles more accessible and actionable across their organisations, particularly for employees who previously found traditional lean methodologies abstract or difficult to apply.

Theme 2: Resilience Through Visibility and Agility

The most frequently cited benefit of digital lean integration was enhanced supply chain visibility, which participants directly linked to improved resilience during disruptions. A COO from an automotive parts manufacturer explained: "During the pandemic and subsequent supply chain disruptions, our digital systems allowed us to quickly identify alternative suppliers and reroute materials. Companies without this visibility were paralysed for weeks." Multiple respondents described how predictive analytics enabled proactive rather than reactive responses to potential disruptions, creating what one participant called "anticipatory resilience."

Theme 3: Cultural and Change Management Challenges

Despite the benefits, participants identified significant challenges in implementing digital lean practices within the Saudi organisational context. Resistance to change was frequently mentioned, with several respondents noting generational differences in technology adoption. A Lean Manager from a food processing company observed: "Our younger employees embraced the digital tools immediately, but senior operators with decades of experience were sceptical. We had to invest heavily in training and demonstrate quick wins to build trust." Language barriers were also noted, as many digital platforms were available only in English, requiring additional localisation efforts or bilingual support.

Theme 4: Sustainability as a Strategic Outcome, Not Just Compliance

Participants increasingly viewed sustainability not merely as regulatory compliance but as a strategic advantage enhanced by digital lean practices. A Director of Operations from a consumer goods manufacturer stated: "Digital monitoring of our energy consumption and waste streams revealed opportunities we never knew existed. We reduced our carbon footprint by 23% while simultaneously cutting costs by 18%." Several respondents connected their sustainability improvements directly to Vision 2030 objectives, viewing environmental performance as both a business imperative and a contribution to national development goals.

Theme 5: The Critical Role of Leadership and Investment

Strong leadership commitment and adequate investment emerged as critical success factors. Organisations with dedicated digital transformation budgets and executive sponsorship achieved significantly better results than those treating digital lean as an incremental IT project. One CEO emphasised: "This isn't about buying software; it's about transforming how we work. That requires sustained investment, patience, and leadership that stays committed through the inevitable challenges." Multiple participants noted that securing adequate funding was easier when digital lean initiatives were framed within the context of Vision 2030 and national economic transformation priorities.

4.11 Integration of Quantitative and Qualitative Findings

The integration of quantitative and qualitative results provided a comprehensive understanding of

digital lean's impact on supply chain resilience and sustainability. While quantitative data demonstrated strong statistical relationships and effect sizes, qualitative insights revealed the mechanisms and contextual factors that explain these relationships. For example, the strong correlation between digital lean and supply chain resilience (r=0.714) is explained through interview data highlighting how real-time visibility, predictive analytics, and agile response capabilities enable organisations to anticipate and respond to disruptions.

The qualitative data also helped explain the variance in adoption rates across different digital technologies. Advanced technologies like blockchain and digital twins showed lower implementation rates (12.8% and 22.5% respectively), not due to lack of interest, but due to perceived complexity, high costs, and uncertainty about return on investment—challenges that emerged clearly in interview discussions but were not captured in survey data.

Furthermore, interview participants provided rich context for understanding the moderating effects of organisational size. Large organisations' stronger benefits from digital lean (as shown in Table 8) were explained by interviewees as resulting from their greater ability to invest in comprehensive digital infrastructure, employ specialised data analytics teams, and absorb implementation costs across larger operational scales.

4.12 Summary of Key Findings

The results of this study provide robust evidence that digital lean practices significantly enhance supply chain resilience and sustainability performance in Saudi organisations. Key findings include: (1) Digital lean implementation directly and positively impacts both supply chain resilience and sustainability, with operational excellence serving as a partial mediator; (2) The integration of digital technologies with traditional lean principles creates synergistic effects that exceed the benefits of either approach alone; (3) Real-time visibility and predictive capabilities enabled by digital tools are the primary mechanisms through which resilience is enhanced; (4) Organizational size moderates the effectiveness of digital lean, with larger organizations achieving stronger impacts; (5) Sector-specific factors influence adoption patterns, with capital-intensive industries showing higher implementation levels; and (6) Cultural factors, leadership commitment, and change management capabilities are critical determinants of successful digital lean implementation in the Saudi context.

5. Discussion

The summary of the main findings is presented above. This study was mainly aimed at validating six hypotheses. All hypotheses were supported by the findings. Each hypothesis is discussed below.

5.1 Digital Lean positively influences supply chain resilience

For this hypothesis, the obtained values were 0.428±0.067, t=6.388, p<0.001. Empirical studies by Piperani, Khan and Yu (2024), Atieh Ali et al. (2024), Hijjawi et al. (2023), Rashid et al. (2024), and Alemsan et al. (2025) support this finding. The work of Piperani, Khan and Yu (2024) was related to the I 4.0 context. Out of these two, each was from Pakistan and Jordan, and one was from Italy. Thus, the hypothesis holds good in varied country contexts. The Italian paper used case studies. Others used surveys.

5.2 Digital Lean enhances operational excellence

The values obtained for this hypothesis were 0.691±0.058, t=11.914, p<0.001. The literature support

for this finding is provided by Lameijer, Pereira and Antony (2021), case studies from the USA, Muhammed et al (2022), a survey from Pakistan, Gomaa (2025), a general paper, Al Dogan and Abd Razak (2024), a survey from Saudi Arabia and Chiarini and Kumar (2021), interviews with managers in Italy. The term Lean 4.0 was used by Gomaa in line with I 4.0.
Operational excellence strengthens supply chain resilience.

The values obtained for this hypothesis were 0.386±0.071, t=5.437, p<0.001. The papers offering support for this finding are two conceptual papers by Gomaa (2025), a survey of Indonesian manufacturing firms by Nugroho, Santosa and Khoa (2025), a survey of manufacturing firms in Ghana by Tetteh et al (2025), and a survey of North American SC specialists by Nkwocha (2024).

5.3 Supply chain resilience contributes to improved sustainability outcomes.

The values obtained for this hypothesis were 0.521±0.064, t=8.141, p<0.001. This finding is supported by the studies of Basuki (2024), Ruiz-Benitez, Lopez and Real (2019), a survey by Ali, Surucu-Balci and Balci (2025), discussions by Malindretos and Binioris (2014), and multiple methods by Singh, Hamid and Garza-Reyes (2023).

5.4 Digital Lean positively impacts sustainability performance.

The values obtained for this hypothesis were 0.267±0.069, t=3.870, p<0.001. This finding is supported by a survey in Egypt by Buhaya and Metwally (2024), a bibliometric literature review by Zekhnini et al (2022), a literature review by Bhattacharya, Nand and Castka (2019), a survey by Presciuttini et al.(2025), related to I 4.0 technologies, and a survey study in Brazil by Mesquita, Lizarelli, & Duarte (2025).

5.5 Operational excellence enhances sustainability outcomes.

The values obtained for this hypothesis were 0.298±0.073, t=4.082, p<0.001. This finding is supported by a phenomenological study by Seifan et al. (2025), by an empirical assessment of Colombian firms by Henríquez-Machado, Muñoz-Villamizar, & Santos (2021), using a literature review and expert suggestions by Moktadir et al. (2020), and a systematic literature review by Henríquez, Muñoz-Villamizar, and Santos (2023).

5.6 Other findings

Digital lean implementation directly and positively impacts both supply chain resilience and sustainability, with operational excellence serving as a partial mediator. Most papers report the mediating effect of supply chain resilience rather than operational excellence. Hence, this aspect needs further examination.

The integration of digital technologies with traditional lean principles creates synergistic effects that exceed the benefits of either approach alone. This finding is supported by Chukwumuanya, Udu, and Okpala (2025), Mondal, Goswami, Gupta, and Sahoo (2026), Valamede and Akkari (2020), Buer, Semini, Strandhagen, and Sgarbossa (2021), and Santos, et al. (2021).

Real-time visibility and predictive capabilities enabled by digital tools are the primary mechanisms through which resilience is enhanced. Support for this finding was obtained from Qiu, Lv, and Chan

(2022) on urban resilience in China, Chan, Jalaluddin, and Asni (2023) on resilience in SMEs, Zhang and Li (2025), Nkomo and Kalisz (2023) and Rădoiu, Bătușaru, and Porancea-Răulea (2024) on resilience in business organisations,

Organisational size moderates the effectiveness of digital lean, with larger organisations achieving stronger impacts. Papers supporting this finding are Chuang, Oliva, and Heim (2019).

Sector-specific factors influence adoption patterns, with capital-intensive industries showing higher implementation levels. This finding, sectoral differences, is supported by Calvino, Criscuolo, Marcolin, and Squicciarini (2018), Avoumatsodo (2023), and Cirera, et al. (2023).

Cultural factors, leadership commitment, and change management capabilities are critical determinants of successful digital lean implementation in the Saudi context. Leadership support was identified by Attar (2023) as one of the four critical factors selected from 14 factors for lean implementation in Saudi SMEs. However, among the 14 factors, organisational culture was a critical factor. According to a survey of 77 firms by Alghuried, Alghuson, Alshehri, Alshehri, and Ali (2024), resistance to change was a barrier to implement digital lean in Saudi maintenance firms. Here, change management capabilities become important. Organisational culture was identified by Inuwa and S. B. A. Rahim (2020) as a success factor for lean implementation in Nigerian firms.

Overall, the literature provides good support for these findings.

5.7 Integration of quantitative findings with qualitative findings

The summary of findings above integrates quantitative and qualitative findings. Further integration with the literature is provided in the Discussion section.

6. Conclusions and Recommendations

6.1 Conclusions

This research aimed to investigate how the integration of Digital Lean practices and Operational Excellence frameworks can strengthen Supply Chain Resilience and advance Sustainability outcomes. All six hypotheses formed from this aim were supported by the findings. There was good literature support for the findings. The results of this study provide robust evidence that digital lean practices significantly enhance supply chain resilience and sustainability performance in Saudi organisations. Key findings include: (1) Digital lean implementation directly and positively impacts both supply chain resilience and sustainability, with operational excellence serving as a partial mediator; (2) The integration of digital technologies with traditional lean principles creates synergistic effects that exceed the benefits of either approach alone; (3) Real-time visibility and predictive capabilities enabled by digital tools are the primary mechanisms through which resilience is enhanced; (4) Organizational size moderates the effectiveness of digital lean, with larger organizations achieving stronger impacts; (5) Sector-specific factors influence adoption patterns, with capital-intensive industries showing higher implementation levels; and (6) Cultural factors, leadership commitment, and change management capabilities are critical determinants of successful digital lean implementation in the Saudi context.

6.2 Recommendations

Most of the evidence presented in the Discussion section is from countries other than Saudi Arabia. This means more research needs to be done on the adoption of Digital Lean for supply chain resilience and sustainability.

Some research on the impact of Saudi culture and social customs on the adoption of Digital Lean for supply chain resilience and sustainability is also need to be done.

Adoption of digital lean is very low in Saudi Arabia. Alghuried, Alghuson, Alshehri, Alshehri, and Ali (2024) found that about 78% of Saudi maintenance business is yet to adopt Lean Six Sigma. According to Albliwi, Antony, Arshed, and Ghadge (2017), the implementation of Lean Six Sigma in Saudi organisations is still in the early stages. Low levels of implementation of Lean Six Sigma in Saudi organisations Albliwi, Antony, Arshed, and Ghadge (2017) and Saudi SMEs were reported by Albliwi and Al-Harbi (2020). Hence, the Saudi government should initiate programmes to increase the adoption level through various types of support.

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