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A machine learning framework for exploring the relationship between supply chain management best practices and agility, risk management, and performance

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A B S T R A C T

This study provides a comprehensive analysis of supply chain management practices based on survey responses from a sample of enterprises. Through descriptive statistics, hypothesis testing, predictive modeling, advanced analytics techniques such as classification, clustering, and association rule mining, the research offers valuable insights into key areas of collaboration, quality management, technology adoption, agility, risk management, and customer responsiveness within supply chains. The findings highlight the importance of strategic integration, proactive problem-solving, customer-centric practices, and agility in meeting changing demands. The study also identifies distinct profiles of practice adoption and reveals intricate relationships between different supply chain practices. Overall, the research contributes to a deeper understanding of supply chain dynamics and offers actionable insights for improving operational performance and strategic decision-making.

1. Introduction

This paper explores how SCM best practices influence organizational performance in SMEs, emphasizing agility, risk management, and technological adoption amidst evolving global markets. Despite extensive research on strategic SCM practices, their specific impact on SMEs, particularly in emerging economies, remains understudied. Analyzing survey data from SMEs in Turkey through descriptive statistics, hypothesis testing, predictive modeling, and advanced analytics, our study aims to uncover insights, identify improvement opportunities, and provide actionable recommendations for enhancing operational efficiency and strategic decision-making.

The current SCM landscape requires agile and risk-managed operations amidst technological advancements and economic shifts. While prior research has largely centered on large enterprises, this study focuses on SMEs, acknowledging their unique challenges such as limited resources and higher vulnerability to market disruptions. Building on supply chain integration and agility theories, we examine how SMEs in Turkey navigate supply chain decisions, integrate advanced SCM practices, and their impact on performance.

Table 1 summarizes key themes in SCM literature, categorizing topics into strategy, design, risk management, and digital transformation. Each theme is backed by seminal and recent studies, reflecting current research trends and advancements.

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Table 1
Studies on SCM

Topic Cluster	Topic Coverage	Examples of Research
Supply Chain Strategy and Design	Focuses on developing strategies for designing and configuring supply chains to meet business objectives efficiently. It involves decisions related to network design, distribution channels, supplier selection, and strategic partnerships.	Chopra & Meindl (2015). Simchi-Levi et al. (2008). Lambert & Cooper (2000). Fawcett et al. (2014).
Supply Chain Planning and Forecasting	Planning and forecasting play a critical role in SCM by ensuring the availability of resources, managing inventory levels, and aligning production with demand. This topic covers methods for demand forecasting, sales and operations planning (S&OP), and inventory optimization.	Tang (2016). Chopra & Sodhi (2004). Wild (2015). Croston (1972).
Supply Chain Collaboration and Integration	Collaboration and integration among supply chain partners are essential for improving coordination, communication, and efficiency. This topic explores approaches to collaboration, such as vendor-managed inventory (VMI), collaborative planning, forecasting, and replenishment (CPFR), and information sharing.	Lee & Whang (2001). Christopher (2016). Croom & Brandon-Jones (2007). Ellram & Cooper (1993).
Inventory Management and Control	Effective inventory management is crucial for balancing supply and demand, minimizing costs, and maximizing service levels. This topic covers techniques for inventory optimization, safety stock management, and inventory control policies like just-in-time (JIT) and economic order quantity (EOQ).	Nahmias (2015). Zipkin (2000). Silver et al. (1998).
Logistics and Transportation	Logistics and transportation are key components of SCM, responsible for the physical movement of goods from suppliers to customers. This topic addresses transportation modes, routing, carrier selection, warehouse management, and distribution center operations.	Coyle et. al. (2016). Ballou (2004). Ballou, Gilbert, & Mukherjee (2000). Langley & Frazelle (1995).
Sustainability and Green Supply Chain	With growing concerns about environmental impact and social responsibility, sustainability has become a prominent topic in SCM literature. This area focuses on reducing carbon emissions, minimizing waste, promoting ethical sourcing practices, and enhancing social responsibility throughout the supply chain.	Seuring & Gold (2013). Sarkis (2013). Srivastava (2007). Seuring & Müller (2008).
Risk Management and Resilience	Supply chains are vulnerable to various risks, including natural disasters, geopolitical events, supplier disruptions, and demand fluctuations. This topic explores risk identification, assessment, mitigation strategies, and building resilience to withstand disruptions.	Chopra & Sodhi (2004). Tang & Tomlin (2008). Handfield & McCormack (2017). Christopher & Peck (2004).
Technology and Digitalization	Advancements in technology, such as big data analytics, blockchain, Internet of Things (IoT), and artificial intelligence (AI), are transforming SCM. This topic examines the impact of technology on supply chain processes, innovation, and digital transformation initiatives.	Laudon & Laudon (2015). Ivanov (2020b). Gunasekaran & Ngai (2004) Wagner & Bode (2008).
Global SCM	Managing global supply chains introduces additional complexities related to cross-border logistics, cultural differences, regulatory compliance, and geopolitical risks. This topic addresses strategies for global sourcing, trade compliance, localization, and managing international supply chain networks.	Lee & Padmanabhan (1997). Wilding (2001). Goldsby & Schrott (2004). Choi & Hong (2002).
Performance Measurement and Continuous Improvement	Measuring supply chain performance is essential for identifying areas of improvement and driving continuous optimization. This topic covers key performance indicators (KPIs), benchmarking, performance measurement frameworks, and methodologies for performance improvement, such as lean management and Six Sigma.	Neely et al. (2005). Krajewski et al. (2015). Farris et al. (2009). Pohlen & Farris (2013).

In the following sections, we detail our survey methodology, discuss key findings in relation to existing SCM literature, and outline implications for SCM theory and practice. Our analysis underscores SCM's critical role and identifies practices that boost SME efficiency and competitiveness.

2. Survey information

To understand the impact of SCM practices on business performance metrics, we conducted a comprehensive survey of enterprises in Turkey. The survey focused on areas such as buyer-supplier collaboration, supply chain integration, total quality management, IT adoption, supply chain agility, risk management, and overall supply chain performance.

2.1 Survey design

The survey included sections to gather general and demographic information, followed by Likert scale items (1=Strongly Disagree to 5=Strongly Agree) to assess SCM practices. These items covered collaboration, integration, management, and technological advancement in supply chains. Detailed survey questions are in Appendix A.

2.2 Survey distribution and responses

The survey, distributed to various businesses across Turkey, yielded 204 completed responses, providing a robust dataset for statistical analysis and hypothesis testing.

2.3 Objectives and hypotheses

The survey aimed to:

- Assess SMC practices in Turkish SMEs.
- Correlate these practices with improvements in operational and strategic performance.
- Explore the impact of integration, collaboration, and technological advancement on agility, risk management, and supply chain efficacy.

The study is structured around several hypotheses, categorized into the following areas:

- **Buyer-Supplier Collaboration (BSC):** Exploring the impact of collaboration on agility, performance, and risk management.
- **Supply Chain Integration (SCI):** Assessing the benefits of integration on performance and collaboration.
- **Total Quality Management (TQM):** Examining the influence of TQM practices on productivity, agility, and performance.
- **Information Technology Adoption (ITA):** Investigating the relationship between IT adoption and enhancements in agility and performance.
- **Supply Chain Agility and Risk Management (SCRM):** Evaluating how agility and proactive risk management contribute to supply chain effectiveness and performance.
- **Supply Chain Performance (SCP):** Analyzing the effects of efficient SCM on customer satisfaction and overall company performance.

Table 2 shows the complete listing of hypotheses and the areas in which they fall.

Table 2
Hypotheses of study.

Hypothesis #	Hypothesis
	BSC
H1	There is a positive correlation between the extent of BSC and supply chain agility.
H2	Increased collaboration with major suppliers positively influences SCP.
H3	Effective collaboration in planning logistics and production schedules correlates with better supply chain risk management.
	SCI
H4	Higher levels of SCI are associated with improved SCP.
H5	Integrated communication networks positively impact BSC.
H6	Sharing market-related information with suppliers and customers
	TQM
H7	Continuous review of production quality standards is positively related to SCP.
H8	Regular maintenance of production equipment through TQM improves overall productivity.
H9	Considering customer complaints for quality improvement contributes to better supply chain agility.
	ITA
H10	Adequate investment in new technology systems positively correlates with supply chain agility.
H11	Adoption of technologically related processes among staff is associated with better SCP.
	SCA
H12	Companies with a higher degree of supply chain agility are better equipped to respond to changes in customer demands.
H13	Flexible production processes contribute to a better ability to forecast and mitigate potential market threats.
	SCRM
H14	Proactive measures to minimize internal and external operational problems are positively related to SCP.
H15	Openly sharing information with suppliers and customers contributes to effective supply chain risk management.
	SCP
H16	Effective SCP positively influences customer service related to product complaints.
H17	A supply chain that enables adaptation and the production of new products contributes to overall company performance.

3. Literature review

3.1 The critical importance of collaboration in SCM

In today's global marketplace, effective SCM is crucial for business success, involving the coordination of activities from sourcing to delivery. Amidst modern supply chain complexities, collaboration is key to driving efficiency, resilience, and innovation. Collaboration among supply chain partners enhances resilience against disruptions, as demonstrated by the COVID-19 pandemic. Companies with strong collaborative relationships adapted better by sharing inventory data and exploring alternative sourcing options. Christopher and Peck (2004) highlight that collaboration fosters proactive risk management and swift responses to challenges. Effective collaboration streamlines supply chain processes by sharing information and aligning objectives, leading to synchronized production, optimized inventory, and reduced lead times. This minimizes delays and excess inventory, resulting in cost savings and enhanced customer satisfaction. Lambert and Cooper (2000) found that collaborative planning, forecasting, and replenishment (CPFR) significantly improve forecast accuracy and reduce stockouts.

Collaboration fosters innovation and continuous improvement by enabling the exchange of insights, best practices, and technological advancements among supply chain partners. This collaborative environment cultivates creativity and facilitates the development of novel solutions to emerging challenges. According to Fawcett *et al.* (2007), collaborative innovation helps companies stay ahead by swiftly adapting to market trends and customer preferences. Ultimately, collaboration in SCM enhances customer satisfaction by enabling faster, reliable, and customized product delivery. This alignment improves service levels, reduces order errors, and enhances responsiveness to customer demands. According to Chopra and Meindl (2007), collaborative supply chains excel in meeting customer expectations, fostering loyalty, and sustaining long-term relationships. Therefore, collaboration is central to effective SCM, driving resilience, efficiency, innovation, and customer satisfaction. Businesses that prioritize collaboration and cultivate strong relationships with supply chain partners are better equipped to navigate uncertainties, seize opportunities, and achieve sustainable growth (Chopra & Meindl, 2007).

3.2 The critical importance of quality management in SCM

Quality management is crucial for the success and sustainability of supply chain operations in today's competitive landscape. Maintaining high standards of quality throughout the supply chain fosters trust, reduces costs, and drives continuous improvement. This study delves into the significance of quality management within the realm of SCM, supported by relevant references. Quality management safeguards brand reputation by ensuring products consistently meet or exceed customer expectations. Maintaining stringent quality standards enhances brand credibility and fosters customer loyalty, crucial for sustaining competitive advantage (Juran & Gryna, 1993). Effective quality management mitigates risks associated with product defects, recalls, and non-compliance by implementing robust control measures. This proactive approach minimizes disruptions and liabilities, protecting brand integrity and preserving shareholder value (Handfield *et al*., 2019). Quality management enhances operational efficiency by reducing waste, rework, and inefficiencies throughout the supply chain. Initiatives like TQM and Lean Six Sigma optimize processes, streamline workflows, eliminate bottlenecks, improving productivity and competitiveness (Oakland, 2003). Quality management promotes a culture of continuous improvement in the supply chain by analyzing performance data to identify defects and drive innovation. This approach supports corrective actions and process refinement, fostering operational excellence and sustained success (Dale, 2003). Quality management is integral to the effectiveness and competitiveness of SCM, upholding brand reputation, mitigating risks, enhancing operational efficiency, and fostering continuous improvement.

3.3 The critical importance of technology adoption in SCM

Technology plays a crucial role in enhancing efficiency, resilience, and innovation within supply chains by improving visibility, optimizing processes, and enabling data-driven decision-making (Kumar *et al*., 2011). Technology adoption optimizes supply chain processes, enhancing efficiency and reducing costs through automation, AI, machine learning (ML), and predictive analytics. Gunasekaran and Ngai (2004) highlight technology's positive impact on supply chain performance, including improved productivity and lower operating costs. Technology enhances collaboration among supply chain partners through cloud platforms, collaborative software, and digital marketplaces, facilitating seamless communication and information sharing across geographies and organizational boundaries. This fosters coordination, agility, and responsiveness within supply chains (Christopher & Towill, 2001). Technology adoption drives innovation in supply chains, enabling adaptation to market dynamics and customer demands through emerging technologies like 3D printing, robotics, and autonomous vehicles. This transformation helps organizations stay competitive, capitalize on trends, and future-proof their operations (Ivanov, 2020a). In essence, technology adoption is essential for unlocking the full potential of SCM in today's digital age. Embracing technology enhances visibility, optimizes processes, fosters collaboration, and drives innovation, leading to competitive advantage and sustainable growth in dynamic markets.

3.4 The critical importance of agility in SCM

Agility is essential for organizations to maintain competitiveness and resilience by promptly adapting to changes, disruptions, and evolving customer demands. Agile supply chains can adjust production schedules, modify product designs, and reallocate resources swiftly to capitalize on opportunities or mitigate risks. Lee (2004) highlights the critical role of agility in meeting dynamic customer demands and achieving competitive advantage. Agile supply chains are adept at navigating disruptions, including natural disasters, geopolitical events, and crises like the COVID-19 pandemic. By emphasizing flexibility and redundancy across sourcing, manufacturing, and distribution processes, agile organizations minimize disruption impacts and ensure continuity of supply. Ivanov and Dolgui (2020) underscore the crucial role of agility in enhancing supply chain resilience and mitigating the effects of disruptions. Agility within supply chains promotes collaboration and innovation by breaking down silos, empowering cross-functional teams, and fostering experimentation. Collaborative relationships with suppliers, partners, and customers allow organizations to leverage collective expertise, share resources, and co-create value-added solutions. Agile supply chains cultivate a culture of continuous improvement and innovation, enabling them to lead in competitive markets and adapt to changing conditions (Fawcett *et al*., 2015). Agility in SCM enhances customer satisfaction by enabling timely delivery, customization, and responsiveness to customer needs. Agile organizations adjust production and distribution processes swiftly to align with demand changes and customer preferences, improving service levels and fostering loyalty. Christopher (2016) underscores agility's role in customer-centricity, impacting brand reputation and market share positively.

Agility is a critical determinant of SCM success, empowering organizations to thrive in dynamic environments. It enables swift responses to market dynamics, effective disruption navigation, collaboration, innovation, and enhanced customer satisfaction, driving sustainable growth and competitiveness.

3.5 The critical importance of risk management in SCM

Risk management in supply chains anticipates, assesses, and mitigates disruptions to prevent operational, financial, and reputational consequences. Organizations proactively implement strategies like diversifying sourcing locations and establishing redundant suppliers to enhance resilience (Sheffi, 2005). Effective risk management safeguards business continuity by minimizing disruptive impacts on supply chain operations through contingency planning, disaster recovery strategies, and supply chain mapping (Chopra & Sodhi, 2004). These measures ensure uninterrupted flow of goods and services, maintaining customer satisfaction, protecting revenue streams, and preserving brand reputation. Risk management in SCM is crucial for protecting financial stability and optimizing resource allocation. Techniques like hedging, insurance, and contract management help mitigate financial risks such as exchange rate fluctuations and cost overruns (Simchi-Levi *et al*., 2003). These strategies enhance cost-effectiveness and support supply chain performance. Robust risk management practices bolster stakeholder confidence in supply chain operations by proactively identifying and mitigating risks (Handfield *et al*., 2019). Transparency, accountability, and adherence to industry standards further enhance perceptions of organizational reliability and resilience among customers, investors, and regulatory authorities. Ultimately, risk management is integral to the effective and sustainable management of supply chains in today's volatile business environment. Proactively identifying, assessing, and mitigating risks enhances supply chain resilience, ensures business continuity, protects financial stability, and fosters stakeholder confidence.

3.6 The critical importance of customer responsiveness in SCM

Customer responsiveness, driven by agility, flexibility, and proactive engagement, is crucial for building and sustaining competitive advantage in supply chains (Mentzer *et al*., 2001). Leveraging real-time data analytics, demand forecasting, and customer feedback allows organizations to anticipate shifts in demand, align operations accordingly, and enhance customer satisfaction and loyalty. Supply chains that prioritize customer responsiveness achieve superior service levels and differentiation in the marketplace by offering personalized experiences, rapid order fulfillment, and flexible delivery options (Tseng & Lin, 2011). Timely responses to inquiries and feedback underscore a commitment to customer satisfaction, enhancing service quality and building brand reputation. Customer responsiveness in supply chains fosters collaboration and alignment among partners toward customer-centric goals (Christopher & Towill, 2001). Sharing information and resources enhances supply chain efficiency, streamlines processes, and reduces lead times. Initiatives like vendor-managed inventory (VMI) and collaborative planning, forecasting, and replenishment (CPFR) enable proactive responses to demand fluctuations, emphasizing the importance of collaboration in achieving customer responsiveness. Customer responsiveness fosters a culture of continuous improvement within supply chains by driving innovation and efficiency enhancements (Dale, 2003). Organizations solicit and act upon customer feedback to identify opportunities for product innovation, process optimization, and service enhancements. Continuous improvement initiatives like lean manufacturing and Six Sigma streamline operations, eliminate waste, and improve responsiveness to customer needs. Customer responsiveness is a critical enabler of success in SCM, allowing organizations to meet dynamic customer demands, enhance service levels, foster collaboration, and drive continuous improvement. Prioritizing customer-centricity and adopting responsive strategies help build lasting relationships, achieve competitive advantage, and thrive in today's marketplace.

4. Methodology

The survey results were analyzed using a ML-based framework that included exploratory data analysis, hypothesis testing, predictive modeling, and advanced analytics methods (refer to Fig. 1). This structured approach facilitated a deeper understanding of the data and enabled comprehensive analysis of the survey findings.

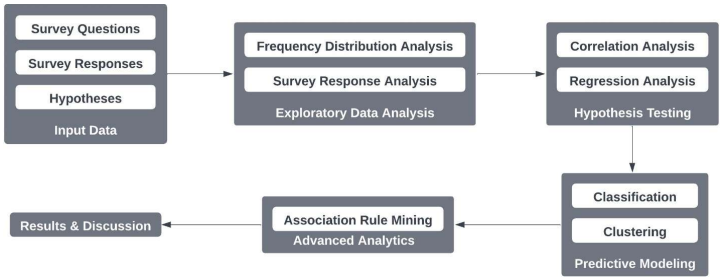

Fig. 1. Block diagram of the methodology.

4.1 Exploratory data analysis

4.1.1 Frequency Distribution Analysis

Fig. 2 displays histograms depicting frequency distributions of survey responses, offering insights into prevalent practices and perspectives among surveyed enterprises. The shapes of these distributions highlight consensus or variation across respondents, aiding in understanding survey findings.

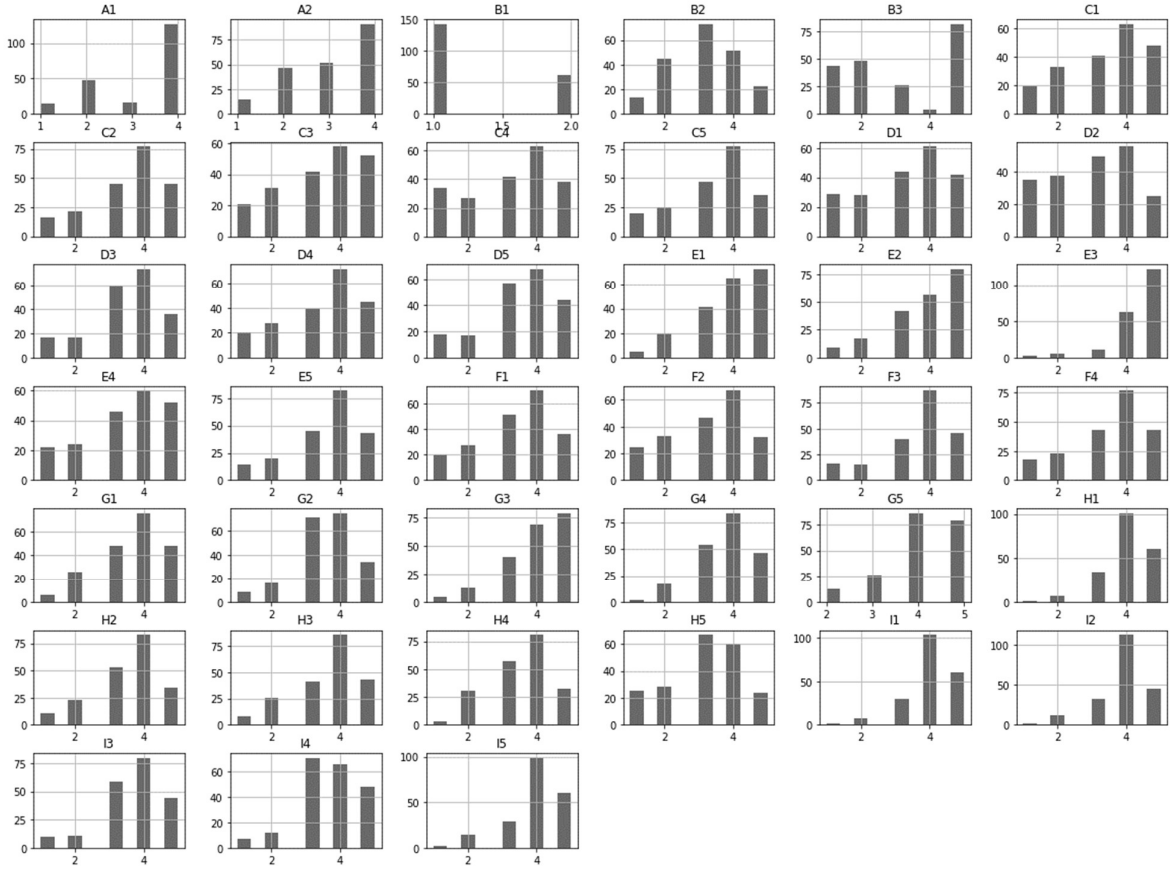

Fig. 2. Frequency distribution of responses to the survey questions.

The frequency distributions of responses show a consensus among participants in key areas. Responses indicate active engagement in logistics, quality problem-solving, and business information sharing with suppliers (refer to survey findings). Similarly, consensus is observed in the integration of communication networks and synchronization of production plans, reflecting understanding of internal and external supply chain processes. Responses indicate strong agreement on TQM practices such as continual review of quality standards, equipment maintenance, and integration of customer feedback for product improvement. Regarding technology adoption, there is general consensus on investment in new technologies and staff adoption of technological processes, with varied responses suggesting different implementation stages across enterprises. Participants predominantly agreed on agility in supply chains, indicating readiness to adapt to customer demand changes, adjust production processes flexibly, and introduce new products promptly (refer to survey findings). Regarding risk management practices, there is a shared view among respondents that enterprises proactively minimize operational issues, share strategic information to manage deficiencies, and closely monitor supplier operations to mitigate supply disruptions. Participants strongly affirmed the effectiveness of supply chains in meeting customer requirements and adapting to order changes, reflecting confidence in their ability to respond and innovate. Overall, the survey data indicate a positive evaluation of supply chain activities with a trend towards progressive practices, despite slight variations in responses suggesting differing experiences across enterprises.

4.1.2 Survey Response Analysis

Descriptive statistics were computed on survey responses to analyze central tendency, dispersion, and distribution of scores for each question item (see Fig. 3). Measures such as mean, median, minimum, maximum, standard deviation, and percentiles were utilized to capture important characteristics and detect outliers, facilitating initial data exploration and insights into respondent tendencies.

Descriptive statistics provide insights into the central tendency and dispersion of responses for each question. For instance, the standard deviation indicates variability, with lower values (e.g., B1) suggesting more consistent responses and higher values (e.g., B3) indicating greater variability. All questions have a minimum score of 1, indicating at least one respondent chose the lowest option. Questions like E3 have higher means closer to the maximum of 5, suggesting general agreement or favorability, whereas lower means (e.g., B1) imply less agreement or lower scores on average. The survey analysis revealed that all questions attained a maximum score of either 4 or 5, indicating that at least one respondent selected the highest possible response for each question. Notably, all 204 respondents provided answers for every question, ensuring complete data without any missing values. Percentile values further contextualized the responses: a median score of 4 for many questions indicated that over half of respondents selected one of the top two responses. The 25th percentile indicated that at least 25% of responses scored 2 or 3, suggesting some variability but generally skewing towards higher scores. Moreover, the 75th percentile demonstrated that 75% of respondents scored questions four or higher, underscoring a strong tendency towards agreement or positive responses throughout the survey.

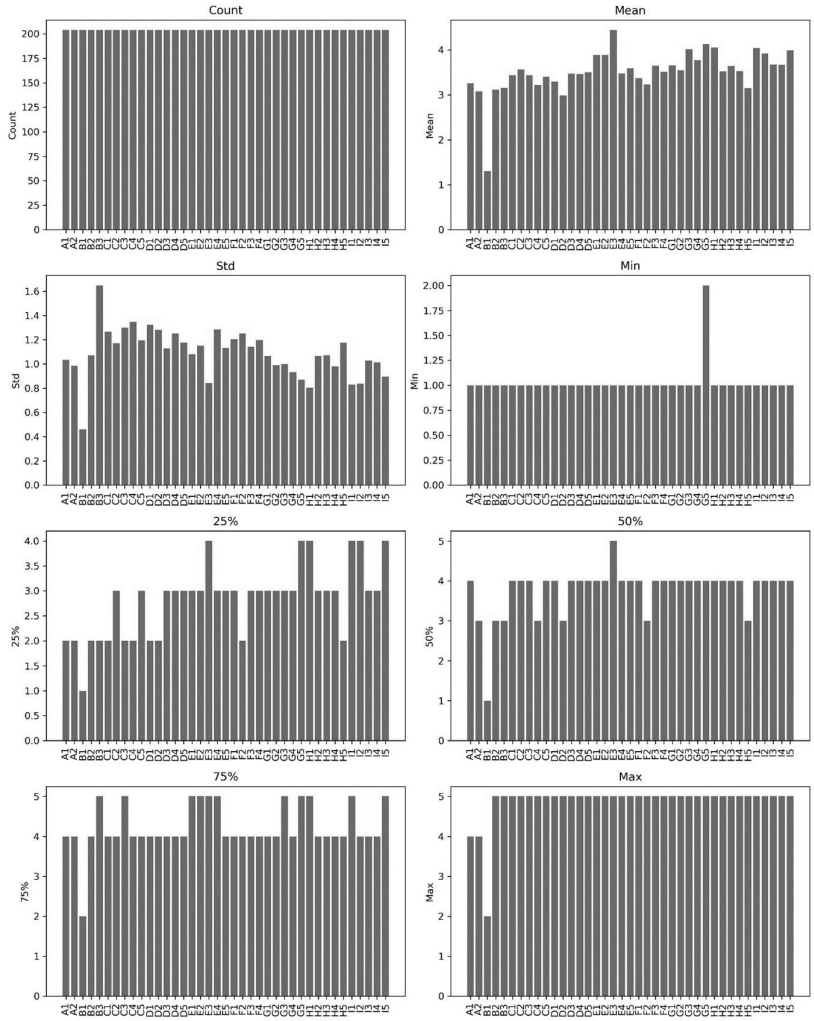

Fig. 3. Visualization of descriptive statistics.

4.2 Hypothesis testing

4.2.1 Correlation analysis

Correlation analysis examines relationships between SCM practices and organizational performance. Fig. 4 displays correlations via a heatmap, revealing associations between survey questions. Table 3 provides the text of correlated questions, offering insights into the interconnectedness of SCM strategies and performance outcomes.

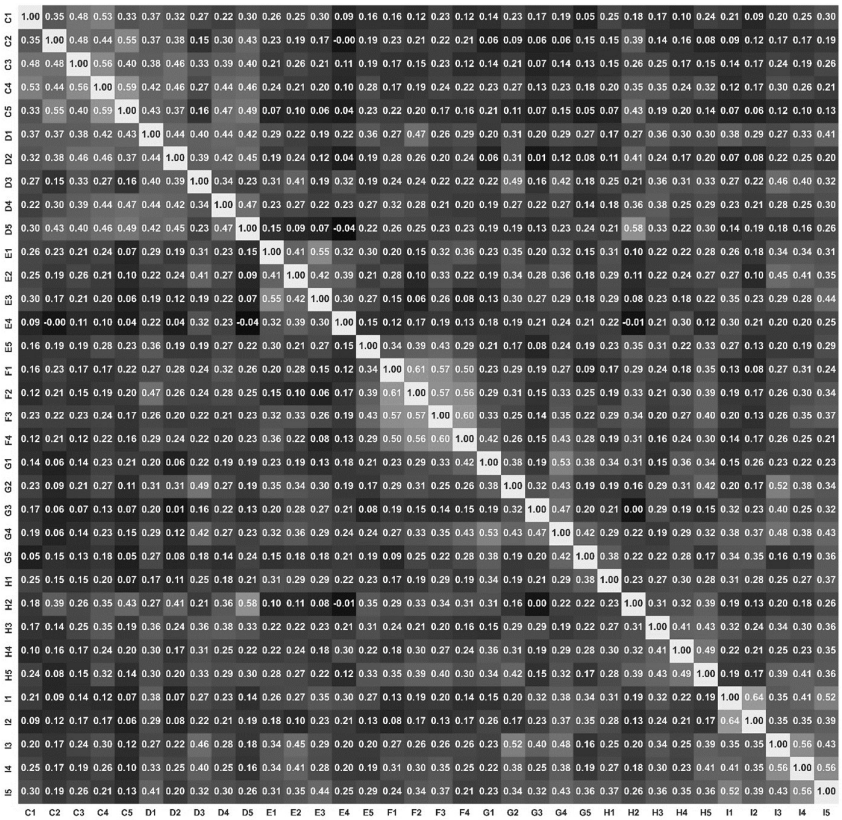

Fig. 4. Map showing the correlations between questions.

Table 3
Questions that correlate with each other

Question 1	Question 2
Our company collaborates with its major suppliers in terms of solving logistics and product quality problems.	Our company collaborates with its major trading partners in setting operation strategies and objectives.
Our company collaborates with its partners in terms of sharing business information.	Our company collaborates with its suppliers in terms of sharing operational and industry knowledge.
Our company collaborates with its suppliers in planning logistics and production schedules.	Our company collaborates with its major trading partners in setting operation strategies and objectives.
Our company collaborates with its major trading partners in setting operation strategies and objectives.	Our company collaborates with its suppliers in terms of sharing operational and industry knowledge.
Our company shares market related information with its major suppliers and customers.	Our company openly shares information with its suppliers and customers to find mutual strategies to deal with possible operational' deficiencies.
Our company continuously reviews the quality standards of its production and operations processes on a regular basis.	Our company takes into consideration customers' complaints as input to improve the quality of our products and services.
Our company has invested adequately in obtaining new technology systems to facilitate the production process.	Our company intends to acquire new information technology systems to share information amongst different departments.
Our company has invested adequately in obtaining new technology systems to facilitate the production process.	Our company emphasizes the adoption of technologically related processes amongst staff.
Our company has invested adequately in obtaining new technology systems to facilitate the production process.	Our company makes use of sophisticated technology to conduct its operations.
Our company intends to acquire new information technology systems to share information amongst different departments.	Our company emphasizes the adoption of technologically related processes amongst staff.
Our company intends to acquire new information technology systems to share information amongst different departments.	Our company makes use of sophisticated technology to conduct its operations.
Our company intends to acquire new information technology systems to share information amongst different departments.	Our company makes use of sophisticated technology to conduct its operations.
Our company is well-equipped to respond to possible changes in its customers' demands.	Our company has the necessary technological and technical capabilities to incorporate additional changes to meet customers' expectations.
The production process of our company is flexible enough to forecast potential threats from the market.	Our supply chain enables us to adapt and produce new products.
Our supply chain enables us to react and meet our customers' requirements effectively.	Our supply chain enables us to consistently respond adequately to changes in our customers/consumer's orders.
Our supply chain enables us to react and meet our customers' requirements effectively.	Our supply chain enables us to improve customer service related to product complaints.
Our supply chain enables us to adapt and produce new products.	Our supply chain helps us to improve the performance of our products.
Our supply chain helps us to improve the performance of our products.	Our supply chain enables us to improve customer service related to product complaints.

Our correlation analysis of survey responses identified strong links between SMEs' collaboration practices with suppliers and trading partners across SCM domains. The findings underscore a strategic emphasis on transparency, information sharing,

and technology adoption to enhance operational efficiencies and external collaborations. SMEs prioritize customer-centric strategies by integrating feedback and adapting to evolving demands, leveraging supplier relationships to boost customer satisfaction. The study highlights the integral role of coordinated collaboration in quality management, logistics optimization, and operational strategy for achieving operational excellence.

4.2.2 Regression analysis

In our research, we utilized ordinary least squares (OLS) regression analysis to investigate how SCM best practices influence supply chain performance (SCP), agility, and risk management. This statistical approach enabled us to quantify the strength and significance of these relationships. Table 4 presents a subset of the regression results, which are further analyzed in subsequent sections of the study.

Table 4
Snippets of results from the regression analysis.

Dependent Variable	R-squared	Significant Variables	Coefficients	P-values
		Hypotheses 1-3		
SCP1 (I1)	0.046	C1	0.1225	0.029
SCP2 (I2)	0.043	N/A	N/A	N/A
SCP3 (I3)	0.109	C4	0.2176	0.004
SCP4 (I4)	0.095	C4	0.1512	0.040
SCP5 (I5)	0.114	C1	0.1598	0.006
		Hypotheses 4-6		
SCP1 (I1)	0.196	SCI1, SCI2, SCI3	0.2268, 0.1307, 0.1297	0.000, 0.011, 0.016
SCP2 (I2)	0.119	SCI1	0.1463	0.005
SCP3 (I3)	0.229	SCI3	0.3655	0.000
SCP4 (I4)	0.198	SCI1, SCI3	0.1342, 0.2602	0.026, 0.000
SCP5 (I5)	0.215	SCI1, SCI3	0.1975, 0.1405	0.000, 0.015
		Hypotheses 7-9		
SCP1 (I1)	0.143	TQM3	0.2530	0.002
SCP2 (I2)	0.058	TQM3	0.1989	0.019
SCP3 (I3)	0.235	TQM1, TQM2	0.1596, 0.3241	0.030, 0.000
SCP4 (I4)	0.208	TQM1, TQM2	0.1770, 0.2768	0.016, 0.000
SCP5 (I5)	0.226	TQM2, TQM3	0.1456, 0.3552	0.009, 0.000
		Hypotheses 10 & 11		
SCP1 (I1)	0.047	N/A	N/A	N/A
SCP2 (I2)	0.041	N/A	N/A	N/A
SCP3 (I3)	0.102	ITA3	0.0772	0.360
SCP4 (I4)	0.143	ITA3	0.1951	0.017
SCP5 (I5)	0.167	ITA2, ITA3	0.1666, 0.2385	0.011, 0.001
		Hypotheses 12 & 13		
SCP1 (I1)	0.216	SCA4, SCA5	0.2072, 0.2315	0.008, 0.001
SCP2 (I2)	0.189	SCA4, SCA5	0.2030, 0.2152	0.011, 0.002
SCP3 (I3)	0.383	SCA2, SCA3, SCA4	0.4060, 0.1619, 0.3330	0.000, 0.016, 0.000
SCP4 (I4)	0.207	SCA2, SCA4	0.2692, 0.2764	0.000, 0.004
SCP5 (I5)	0.274	SCA2, SCA4, SCA5	0.1718, 0.2333, 0.2401	0.007, 0.004, 0.001
		Hypotheses 14 & 15		
SCP1 (I1)	0.164	SCRM1, SCRM3	0.2373, 0.1772	0.001, 0.003
SCP2 (I2)	0.111	SCRM1	0.2191	0.004
SCP3 (I3)	0.201	SCRM1, SCRM3, SCRM5	0.1502, 0.1804, 0.2426	0.087, 0.012, 0.001
SCP4 (I4)	0.206	SCRM1, SCRM5	0.1998, 0.2776	0.020, 0.000
SCP5 (I5)	0.255	SCRM1, SCRM3, SCRM5	0.2634, 0.1411, 0.1054	0.000, 0.019, 0.071
		Hypothesis 16		
SCP5 (I5)	0.426	SCP1, SCP4	0.3602, 0.3210	0.000, 0.000
		Hypothesis 17		
SCP1 (I1)	0.456	SCP2, SCP4	0.5596, 0.1549	0.000, 0.004

The findings underscore the critical role of strategic supply chain integration (SCI) in enhancing performance across various metrics. Effective communication networks facilitating seamless information sharing, coupled with deep operational process integration among supply chain partners, consistently showed significant positive impacts on performance outcomes. This highlights the importance of well-coordinated operational processes and fluid information sharing as key to supply chain success. Additionally, active collaboration among partners in resolving logistics and quality challenges emerged as a pivotal driver of superior performance. Such collaborative problem-solving creates a synergistic environment where collective expertise addresses operational hurdles, ultimately yielding improved outcomes.

Consistently integrating customer complaints and feedback into quality improvement initiatives significantly enhances performance across various metrics, affirming the critical role of customer perspectives in effective quality management and supply chain excellence. Regular maintenance of production equipment also shows substantial positive effects on productivity and overall performance levels. However, the impact of continuously reviewing and updating quality standards was less uniform, suggesting a need for deeper exploration into their implementation and organizational perception.

The overall impact of technology investment and adoption on supply chain performance (SCP) dimensions was found to be modest. While specific aspects of technology adoption, such as integrating technological processes among staff, showed positive influences on certain performance outcomes, the broader effect was limited. This underscores the importance of thoughtful implementation and integration of technology with existing processes, as well as the role of staff training in maximizing the benefits of IT investments in SCM.

The regression analysis highlighted the pivotal role of flexibility in production processes and responsiveness to customer demands in enhancing supply chain performance (SCP). The ability to meet customer expectations promptly and maintain flexible production processes consistently showed positive and significant impacts, underscoring the benefits of supply chain agility. Investments aimed at enhancing agility through flexible production capabilities and customer responsiveness are therefore crucial for achieving substantial performance improvements and should be prioritized in supply chain strategies.

The study highlighted proactive risk management's critical role in enhancing supply chain performance (SCP). Measures to minimize operational issues, ongoing monitoring, and transparent information sharing with suppliers and customers were identified as beneficial practices. These insights underscore the importance of robust risk management frameworks, emphasizing proactive mitigation, operational monitoring, and effective partner communication.

The analysis found that effective supply chain performance (SCP) significantly enhances customer service related to product complaints, underscoring its role in achieving high satisfaction and service quality. The study also validated SCP's critical impact on overall company performance in SCM, emphasizing the need for targeted improvements in responsiveness, reliability, and operational efficiency to enhance broader supply chain outcomes and organizational success.

4.3 Predictive modeling

4.3.1 Classification

This paper has primarily analyzed survey data from Turkish SMEs using traditional statistical methods. Shifting focus, the upcoming sections will explore how ML methods can enhance analysis of similar survey data. The first ML method discussed will be classification. Classification, a fundamental supervised task in ML, entails predicting the correct label or class for input data. In this study, we employed logistic regression for a classification system aimed at predicting organizational performance from survey data. The goal is to convert raw data into actionable insights, aiding in the identification of performance trends and facilitating data-driven decision-making. This approach supports strategic planning and operational adjustments across organizations.

For our research, developing the classification system involves key steps: first, loading and preliminarily examining survey data from three CSV files. This phase ensures data completeness, consistency, and structure comprehension. Next, aggregating response frequencies to calculate mean responses per question simplifies data complexity, facilitating trend analysis across survey sections. These mean responses are then mapped to hypotheses, linking empirical data with theoretical constructs.

A logistic regression model is employed to classify survey responses into high or low performance categories based on a threshold mean response score. This model was selected for its effectiveness in handling binary outcomes and its capacity to offer clear interpretations directly tied to survey questions and organizational performance metrics.

The classification system's results are validated via cross-validation, affirming the logistic regression model's robustness and reliability. With an accuracy score of 94.29%, the model effectively distinguishes between high and low performance indicators in survey responses. This categorization offers immediate insights into organizational strengths and areas needing improvement, validating hypotheses about performance determinants.

4.3.2 Clustering

In contrast to classification, clustering in ML identifies natural data groupings, revealing patterns not obvious through direct observation. Our research applies k-Means clustering to SME survey responses on SCM, aiming to uncover adoption and perception patterns. This enables tailored strategies that cater to varied organizational profiles. To achieve optimal performance with the k-Means algorithm, selecting the right number of clusters, k, is crucial. Our research uses the silhouette method to determine this, balancing visual and numerical approaches. The silhouette method utilizes silhouette scores, measuring how well each object fits its own cluster compared to others (Yuan & Yang, 2019). Scores range from -1 to 1: closer to 1 indicates a well-defined cluster, 0 suggests bordering clusters, and near -1 may indicate misassignment (Yuan & Yang, 2019).

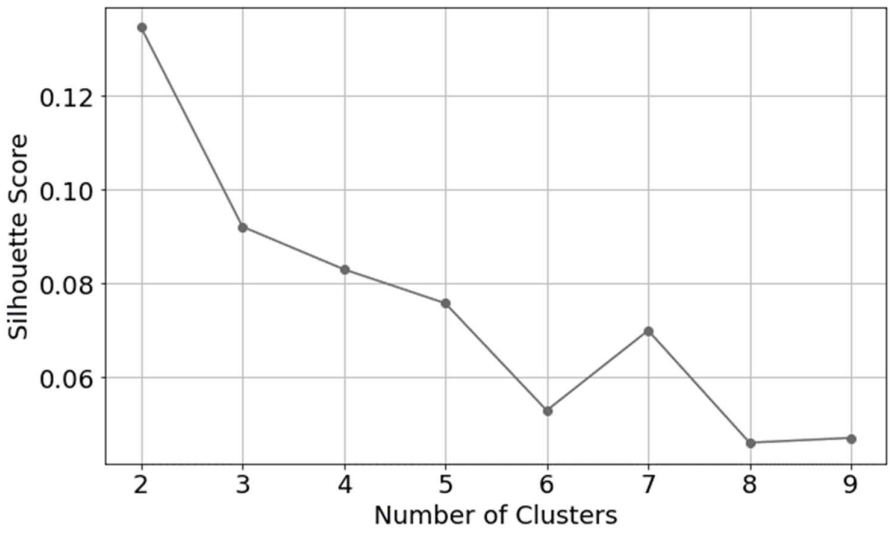

Fig. 5. Silhouette scores for varying numbers of clusters.

The optimal number of clusters identified was two, based on the highest silhouette score, indicating distinct division in response patterns (see Fig. 5). Examination of cluster centroids revealed significant differences in technology adoption, collaborative planning, and quality management practices (Salam & Yaqub, 2023). Cluster 1 showed stronger alignment with advanced supply chain practices compared to Cluster 0, highlighting proactive integration of technology and collaboration.
Cluster 0 showed lower scores in technology adoption and collaboration, indicating SMEs with developing capabilities in these areas. In contrast, Cluster 1 demonstrated strong alignment with modern supply chain practices, suggesting effective use of integrated technologies and collaborations. These insights support targeted strategies: Cluster 0 might benefit from focused developmental programs in technology and collaboration, while Cluster 1 should consider advanced training to maintain leadership in the industry.

4.4 Association rule mining

While correlation analysis and clustering reveal patterns in survey data, association rule mining offers a deeper exploration. This data mining technique identifies frequent item sets and derives rules to predict item occurrences based on others. Rules are evaluated using confidence (frequency of Y given X) and lift (comparison of Y's occurrence with and without X).

This section discusses association rule mining, specifically the Apriori method, used for advanced analysis of survey data similar to our research. Apriori operates on the principle that all non-empty subsets of a frequent itemset must also be frequent, known as the Apriori property.

To prepare for the Apriori algorithm, we transformed survey responses into categorical data and encoded them into a binary one-hot format using the Pandas library in Python. The algorithm was then applied to identify frequent item sets, using a minimum support threshold of 10%. Rules were generated and evaluated based on confidence and lift metrics, with thresholds set to highlight significant and reliable rules.

The analysis revealed key associations supporting our hypotheses. For instance, {Strongly Disagree with B1} -> {Agree with A1} showed near-independence with a lift close to 1, indicating demographic disagreement doesn't significantly affect perceived business type. In contrast, a stronger association was found between agreeing on integrated communication networks (A1) and positive attitudes towards technology adoption (I1), with a lift slightly above 1, suggesting a subtle but positive correlation. This example of association rule mining supports hypothesized relationships and identifies areas where expected associations may differ.

5. Conclusion

Our findings underscore the critical role of effective SCM practices in enhancing SME performance metrics. Technological adoption, strategic collaborations, and robust quality management systems are essential for fostering supply chain agility and risk management, leading to improved operational efficiency and competitive advantage. We advocate for SMEs to invest in integrated SCM solutions and adaptive strategies that address market dynamics and supply chain challenges. Emphasizing continuous improvement and alignment with advanced SCM practices can drive operational excellence and sustainable growth. Future research should explore longitudinal impacts and validate these findings across diverse geographical contexts.

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Appendix A

Survey Questions

SECTION A: GENERAL INFORMATION

In this section we would like to find out information regarding the overall profile of your company. Please place a cross (x) in the appropriate block.

A1	**Type of business**	Cooperative	Sole proprietor	Close corporation	Private company	Partnership
	(x)					

A2	**Nature of your business**	Mining	Manufacturing	Retail	Transport	Tourism	Finance/ insurance	Agricul-ture
	(x)							
Other (please indicate)								

SECTION B: DEMOGRAPHIC PROFILE OF RESPONDENTS

In this section we would like to find out personal details about yourself. Please place a cross (x) in the appropriate block.

B1	**Gender**	Male	Female
	(x)		

B2	**Race**	African	White	Indian/Asian	Coloured
	(x)				
Other (please indicate)					

B3	**Age group**	18-25	26-35	36-45	46-55	56+
	(x)					

SECTION C: BUYER-SUPPLIER COLLABORATION

We would like to find out a little more about your views towards buyer supplier collaboration. Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

BSC_1	Our company collaborates with its major suppliers in terms of solving logistics and product quality problems.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
BSC_2	Our company collaborates with its partners in terms of sharing business information.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
BSC_3	Our company collaborates with its suppliers in planning logistics and production schedules.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
BSC_4	Our company collaborates with its major trading partners in setting operation strategies and objectives.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
BSC_5	Our company collaborates with its suppliers in terms of sharing operational and industry knowledge.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**

SECTION D: SUPPLY CHAIN INTEGRATION

We would like to find out a little more about your views towards supply chain integration. Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

SCI 1	Our company has an integrated communication network with all its business functions to enable an effective sharing and flow of information across all departments.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCI 2	Our company shares production plans and schedules with its suppliers.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCI 3	Our company integrates majority of its operations processes from raw material through to delivery.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCI 4	Our company shares forecasting activities with its major suppliers to ensure adequate inventory management.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCI 5	Our company shares market related information with its major suppliers and customers.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**

SECTION E: TOTAL QUALITY MANAGEMENT (TQM)

We would like to find out a little more about your views towards total quality management (TQM). Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

TQM 1	Our company continuously reviews the quality standards of its production and operations processes on a regular basis.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
TQM 2	Our production equipment undergoes regular maintenance in order to improve its overall productivities.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
TQM 3	Our company takes into consideration customers' complaints as input to improve the quality of our products and services.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
TQM 4	Our production' times are maintained through just-in-time strategy to facilitate a quick response to customers' inquiries.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
TQM 5	Our company is actively engaged in providing quality training courses to its employees.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**

SECTION F: INFORMATION TECHNOLOGY (IT) ADOPTION

We would like to find out a little more about your views towards supply chain agility. Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

ITA 1	Our company has invested adequately in obtaining new technology systems to facilitate the production process.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
ITA 2	Our company intends to acquire new information technology systems to share information amongst different departments.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
ITA 3	Our company emphasises the adoption of technologically related processes amongst staff.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
ITA 4	Our company makes use of sophisticated technology to conduct its operations.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**

SECTION G: SUPPLY CHAIN AGILITY

We would like to find out a little more about your views towards supply chain agility. Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

SCA $_1$	Our company is well-equipped to respond to possible changes in its customers' demands.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCA $_2$	The production process of our company is flexible enough to forecast potential threats from the market.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCA $_3$	Our company strives to ensure timely introduction of new products to meet market requirements and expectations.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCA $_4$	Our company has the necessary technological and technical capabilities to incorporate additional changes to meet customers' expectations.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCA $_5$	Our company has the capability to meet customers' expectations in a timely manner in terms of on-time delivery.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**

SECTION H: SUPPLY CHAIN RISK MANAGEMENT

We would like to find out a little more about your views towards supply chain risk management. Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

SCRM$_1$	Our company strives to minimise potential internal and external operation problems that can negatively affect its operations.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCRM $_2$	Our company openly shares information with its suppliers and customers to find mutual strategies to deal with possible operational' deficiencies.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCRM $_3$	Our company consistently monitors the operations of our suppliers to minimise potential distortions in supplies/deliveries.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCRM $_4$	Our company has proper contingency plans to mitigate/handle sudden market changes.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCRM $_5$	Our company minimises risks related to customers' demands by adopting late product differentiation approach.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**

SECTION I: SUPPLY CHAIN PERFORMANCE

We would like to find out a little more about your views towards supply chain performance. Please indicate the extent to which you agree or disagree by ticking the corresponding number between 1 (Strongly disagree) and 5 (Strongly agree). With 2 (Disagree), 3 (Neutral/No opinion) and 4 (Agree).

SCP$_1$	Our supply chain enables us to react and meet our customers' requirements effectively.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCP $_2$	Our supply chain enables us to consistently respond adequately to changes in our customers/consumer's orders.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCP $_3$	Our supply chain enables us to adapt and produce new products.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCP $_4$	Our supply chain helps us to improve the performance of our products.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**
SCP $_5$	Our supply chain enables us to improve customer service related to product complaints.	**Strongly disagree**	1	2	3	4	5	**Strongly agree**